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CONTENTS

REFERENCE SECTION

IGR TRANSLITERATION OF RUSSIAN

The AGI Translation Office has adopted the Cyrillic transliteration recommended by the U. S. Department of the Interior, Board on Geographic Names, Washington, D.C.

Alphabet		transliteration
А	а	a
Б	б	b
В	в	v
Г	г	g
Д	д	d
Е	е	e, ye(1)
Ё	ё	ë, yë
Ж	ж	zh
З	з	z
И	и	i
Й	й	y
К	к	k
Л	л	l
М	м	m
Н	н	n
О	о	o
П	п	p
Р	р	r
С	с	s
Т	т	t
У	у	u
Ф	ф	f
Х	х	kh
Ц	ц	ts
Ч	ч	ch
Ш	ш	sh
Щ	щ	shch
Ъ	ъ	"
Ы	ы	y
Ь	ь	'
Э	э	e
Ю	ю	yu
Я	я	ya

NOTES:

(1) "ye" initially, after vowels, and after ъ,ь; "e" elsewhere; when written as "ë" in Russian, transliterate as "yë" or "ë".

Well-known place and personal names that have wide acceptance will be used. Some translations may include elements of previous German transliteration from the Russian; this occurs in IGR most commonly in maps and lists of references. The reader's attention is called to the following variations between German and English systems which may cause confusion when trying to check back to original Russian sources.

German	English
w	v
s	z
ch	kh
tz	ts
tsch	ch
sch	sh
schtsch	shch
ja	ya
ju	yu

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ALKALIC ULTRABASIC ROCK AND CARBONATITES IN THE U.S.S.R.

by

S.I. Tomkeieff [1]

ABSTRACT

This article gives a brief review of recent Soviet publications on the subject of alkalic ultrabasic rocks associated with carbonatites in the Kola Peninsula and Siberia. These rocks are found mainly as complexes infilling diatremes or cycloliths, and, as a rule consist of one, two or more rock series, of which the principal are the following: 1) Normal calc-alkali or alkali series ranging from ultrabasic to intermediate, 2) per-alkalic jacupirangite-urtite series, 3) nepheline syenites and fenites, and 4) carbonatites.

Taking into consideration this Soviet work and using the Kola Peninsula and Siberian material it seems possible to produce a genetic scheme embracing all the four series, if it is accepted that, in addition to the crystallization-differentiation, there is a diffusion-differentiation, conditioned by an upward thermodiffusion of alkalies and volatiles, and among these, more particularly, carbon dioxide and water. Such a diffusion-differentiation, would promote the formation of the per-alkalic magma from the normal alkalic magma. The newly formed jacupirangite-urtite magma being highly chemically active, would give rise to two parallel processes: -nephelinitization and carbonatization. These two processes would be conditioned by an exchange reaction between the alkali carbonates present in the fluidal fraction of the magma and the calcium and magnesium silicates present either as minerals or molecules in the magma. Such a reaction can be visualized as:

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + Na_2CO_3 = \underset{\text{nepheline}}{2NaAlSiO_4} + \underset{\text{calcite}}{CaCO_3}$$

The production of a nepheline molecule would lead to an intensive alkali auto- and hetero-metasomatism, transforming the granitic country rock first to fenite and this to a mobilized fenite and eventually to nepheline syenite. At the same time the production of calcium, magnesium and iron carbonates, would lead to an equally intensive carbonate auto- and hetero- metasomatism. The remaining solution would give rise to nephelinoliths and carbonatites. Postulating alkali carbonates as the transported material during the diffusion-differentiation, one must abandon the idea of an existing "carbonatite magma" in favor of "magmatic carbonates" forming through an exchange reaction during the hydrothermal stages of the magmatic consolidation. --Author.

* * *

PART 1: GENERAL DESCRIPTION

The Kola Peninsula, which occupies the northeastern part of the Fennoscandian shield, consists mainly of Precambrian metamorphic and igneous rocks intruded by later granites and gabbros and other sub-alkalic rocks, principally of early Paleozoic age. Of a slightly later age are the intrusive alkalic granites, alkaline syenites and alkaline ultrabasites often associated with carbonatites. Of these, probably the best known are the large nepheline syenite intrusive massifs of the Khibina Tundras (Umptek) and of the Lovozero Tundras (Luyavrurt). Formerly it was assumed by Gerling and Starik (1942) that these two massifs were of upper Paleozoic age, while the minor ultrabasic intrusions were of the lower Paleozoic age, but recent age determinations by Semenov and Shuba (1959) have shown that all the alkalic intrusions in the Kola Peninsula are of approximately the same age, namely 350 million years (Silurian).

These two large intrusive complexes, the Khibina Tundras and the Lovozero Tundras were "scientifically discovered" during the last decades of the 19th century by W. Ramsay and V. Hackman (Ramsay and Hackman, 1894; Ramsay, 1899), but a new period in their study was opened by the construction of the Murmansk railway in 1917 and during the first decade of this new period much new work was done by a large number of geologists, including A. E. Fersman, B. M. Kupletsky, V. I. Vlodavetz, D. S. Belyankin, A. A. Polkanov, N. A. Eliseev, E. Krank and T. Brenner. The interest shown by petrologists in the alkalic rocks of the Kola Peninsula and Finland is made manifest in the names of many igneous rocks such as ijolite, imandrite, khibinite, kovdorite, lestiwarite, lujavrite, lujavritite, rischorrite, tavite, turjaite, turjite, umptekite and urtite.

In the present article I propose to give a brief account of the most recent work published in the U. S. S. R. on alkalic ultrabasic rocks and

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carbonatites. Thus, after a brief account of the classical areas of the Khibina and Lovozero Tundras, I will discuss the other occurrences in the Kola Peninsula and Siberia. With few exceptions, I shall abstain from drawing comparisons with other well known occurrences of these rocks in other parts of the world, but I shall use appropriate material in the world's literature on this subject in drawing my conclusions as to the probable origin of these rocks.

In the Kola Peninsula one can distinguish the large nepheline syenite massifs of the Khibina Tundras and the Lovozero Tundras as well as a number of minor alkalic intrusive complexes, which as discovered up to date, number 13 localities, apparently occurring in four east-to-west belts (Table 1). Unfortunately I have been unable to obtain any published material relating to four of these localities, as indicated Table 1.

their eastern ends. The outer contact surface of the intrusive rocks against the country rocks is rather steep, inclined outwards or inwards as the case may be, or even in places vertical. Thus this surface may represent either an "up-cone" or a "down-cone". The igneous complex itself, in both massifs is represented by a layered series, with bands dipping towards the center of the complex, with dips varying from a few degrees to 30 degrees. The eccentric disposition of the ovals is due to the unequal thickness of the major layer, i. e. thick to the west and thin to the east.

The most outstanding structural-textural feature characterizing the intrusive rocks of these two complexes is the ubiquitous banding associated with planar and linear flow texture, as marked by the platy crystals of feldspars (trachytic texture) and by elongation of the

TABLE 1. Massifs of alkalic igneous rocks, Kola Peninsula

Locality		Principal rock groups			
		Peridotite-basalt-andesite	Urtite-Jacupirangite	Syenites and nepheline syenites	Carbonatites
Belt I	1. Chagve-Uaiv	-	?	major	-
Belt II	2. Sebl-Yarvi	-	(no information)		
	3. Gremyakha-Vyrmes	major	minor	minor	-
	(Khibina and Lovozero)	-	minor	major	-
Belt III	4. Kovdozero	minor	major	-	-
	5. Afrikanda	minor	major	-	minor
	6. Ozernaya Varaka	minor	major	minor	minor
	7. Lesnaya Varaka	-	major	-	-
	8. Salmagorsk	(no information)			
	9. Pesochny				
Belt IV	10. Kuolo-Yarvi	(no information)			
	11. Vuori-Yarvi	major	major	minor	minor
	12. Kovdorozero	-	minor	minor	minor
	13. Turyi Peninsula	minor	minor	minor	minor

NOTE: Relative volumes of the several rocks types occurring within the massif are indicated as either "major" or "minor" in occurrence.

The igneous complex of the Khibina Tundras, also called Umptek, is oval in plan and in size is about 40 km by 35 km. It is situated between lakes Imandra and Umbozero. The igneous complex of the Lovozero Tundras, also called Luyavr-Urt, is situated to the east of the Khibina Tundras, between lakes Umbozero and Lovozero. It is also oval in plan and in size is about 30 km by 20 km. On the map (fig. 1) these two intrusive complexes are shaded with a pattern of crosses.

Looking at the geological-structural maps of these two complexes one can see at once that the petrological varieties of the component rocks are bounded by a series of eccentric ovals coming close together or touching each other at

pyroxene needles. Kupletsky (1932) calls this feature "crystallization layering", while Wager and Deer (1939) apply to such complexes the term "layered series". This all-pervasive flow structure, ranging from very thick bands to very thin laminae, is also a characteristic of many other alkalic igneous complexes in the Kola Peninsula, such as that of Gremyakha-Vyrmes, described by Polkanov and Eliseev (1941). In the Khibina complex the flow structure is accentuated by flow schlieren and block and breccia structures, described by Eliseev, Ozhinsky and Volodin (1939).

The Russian geologists hold differing views about the large-scale structure of the Khibina and Lovozero igneous massifs. The horseshoe

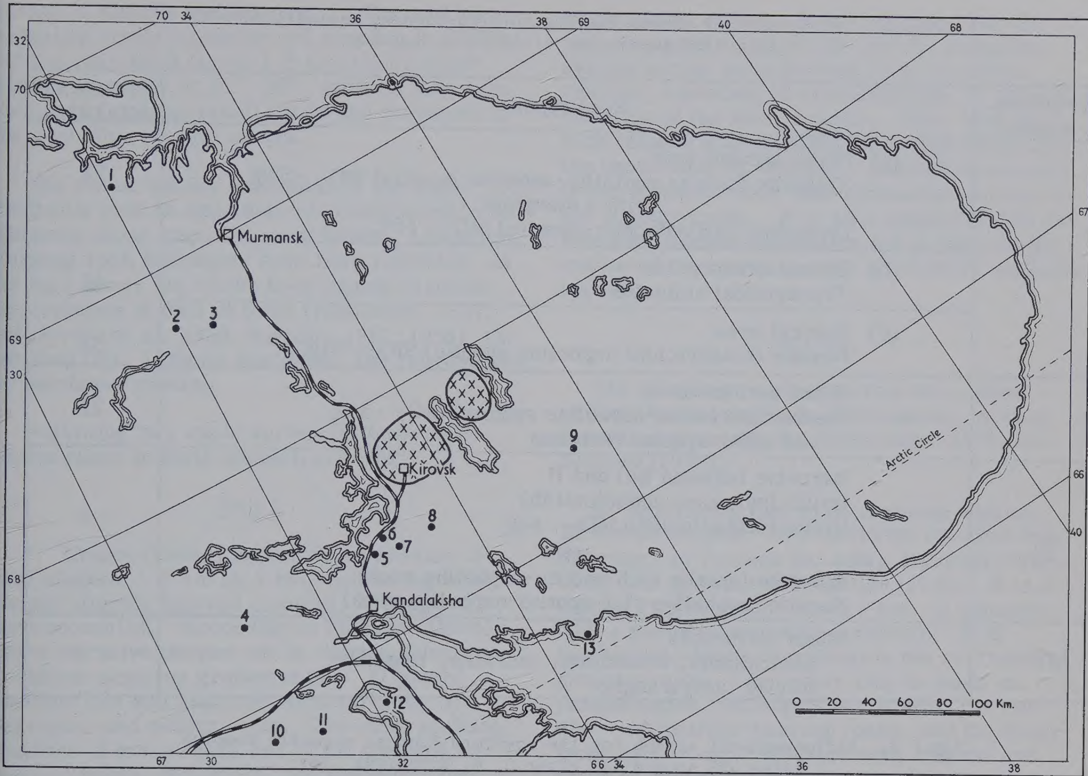

FIGURE 1. Map of the Kola Peninsula showing the east-west belts of alkalic intrusions

plan of the rock units, the centripetal dips, and the all-pervasive flow structure suggest, on the one hand, comparison with the Oslo district subvolcanic caldrons, and on the other hand, with complex-layered laccoliths or lopoliths. The Khibina and Lovozero massifs probably represent a deeper level of erosion than the caldron of the Oslo district, in which the only caldron having saucer-shaped bands is the Sande caldron, described by Oftedahl (1953) and mentioned by Tomkeieff (1957). Eliseev (1936) assumes that in the Kola massifs the banding and flow texture are due to a flow of a heterogenous magma during the process of infilling of a cavity in the earth's crust. Bussen and Sakharov (1958) apply the name "complex ethmolith" to the Lovozero massif.

In my opinion, for a better comparison with these two complexes we should go to the Skaergaard layered intrusion in east Greenland, described by Wager and Deer (1939). This particular layered complex is intruded into a funnel-cone cavity. Wager and Brown (1957) discuss in detail such funnel-shaped layered intrusions, called "funnel intrusions" by Balk in 1927. The Skaergaard funnel intrusion, like those of Khibina and Lovozero, is also characterized by a fluxion structure ranging from very broad bands to a minute lamination. All layering produces a structural mass similar to a "pile of saucers". This characteristic combination of layered structure with a conical shape of the whole complex, suggests the possibility of applying to it a new term "stromoconolith", based on three Greek words "stroma" signifying a layer, "chono" or "cono" a funnel, and "lith" pertaining to rocks. "Stromoconolith", as a specific term for a type of igneous intrusion must not be confused with a rarely used term "Stromatolith", applied by W. G. Foye in 1916 to an igneous sill interbanded with sedimentary strata, or with "conolith", also a rarely used term applied by R. A. Daly to an irregularly shaped intrusion. The term "stromoconolith" would obviously apply and the up-cone, down-cone and also to the cylindrical shaped intrusive layered bodies.

Stromoconolith represents a banded roof intrusion, the "pile of saucers" structure of which suggests that this roof intrusion sagged in its central part, probably due to the removal of the magma from the underlying reservoir. One can also postulate that the stromoconolith was fed through the ring dike openings between the sinking crusted frustrum and the circular fault delimiting the complex. Thus cyclic magmatic complexes — "cycloliths", for short, in their upper level of erosion appear as stromoconoliths, and in the lower level of erosion — ring dike complexes. An uppermost level of erosion, in certain cases, may reveal a volcanic caldera. Cone sheets which are

TABLE 2. Petrographical scheme for the Khibina Tundras magmatic complex (area 1385 square km) after B. M. Kupletsky

Sequence stages	Rock types	Percent of total area
I	(a) Outer arcuate zone Khibinite (coarse eudialite-nepeline syenite) SiO_2 - 53% with a marginal Umptekite (arfvedsonite-syenite) SiO_2 - 66%	22
	(b) Second arcuate zone Trachytoidal khibinite	18
	(c) Central area Foyaite (trachytoidal nepheline syenite) SiO_2 - 51%	33
II	Third arcuate zone Rischorrite (mica-nepheline syenite) SiO_2 - 54% and other syenite varieties	22
III	Intrusive between I(c) and II Ijolite (pyroxene nephelinolith) Urtite (nephelinolith) SiO_2 - 44% with Apaneite (apatite rich apatite-nepheline rock) Neapite (nepheline rich apatite-nepheline rock)	4
IV	Minor intrusions Monchiquite, shonkinite, theralite, tinguaite, olivine jacupirangite	1

TABLE 3. Petrographical scheme for the Lovozero Tundras magmatic complex (area 485 square km) after O. A. Vorobieva

Sequence stages	Rock types	Percent of total area
I	(a) Lower part Lujavrite (trachytoidal khibinite) SiO_2 - 52%	42.7
	(b) Upper part Eudialyte lujavrite	49.1
II	Foayaite and other varieties of nepheline syenites	1.8
III	Urtite (nephinolith) Tavite (sodalite ijolite) SiO_2 - 46% Foyaite	6.4
IV	Minor intrusions Monchiquite, tinguaite and others	-

produced by the up-bulge of the earth's crust in the region of a cyclolith, are usually associated with the ring dikes level.

Thus the Khibina and Lovozero cycloliths belong to the type of stromoconolith or banded roof intrusions. Other alkalic complexes in the Kola peninsula may also belong to this type, which get others to belong to the types of diatremes or explosive pipes.

The existing literature on the Khibina and Lovozero massifs is extensive, but the fundamental data are contained in the publications by Ramsay (1899), Ramsay and Hackman (1894), Kupletsky (1932, 1936a, 1936b, 1937, 1938a, 1938b), Fersman (1937), Eliseev (1936), Eliseev, Ozhinsky and Volodin (1939), Polkanov (1938, 1947) and Bussen and Sakharov (1958). These two massifs consist mainly of different varieties of nepheline syenite. Several sequence stages have been proposed, and I present in Tables 2 and 3 the two schemes as given in the volume edited by Fersman (1937). In a number of cases a rational rock name is appended in parentheses, sometimes accompanied by the average percentage of silica.

Tables 2 and 3 show that well over 90 percent of the total rocks of these two complexes belong to different varieties of nepheline syenites, but apparently representing a separate intrusion, are the rocks belonging to the urtite-jacupirangite series and to the apatite-nepheline series. The last series seems to be a substitute for the carbonatite series, almost entirely

absent in Khibina and Lovosero. The apatite-nepheline rocks (apaneite and neapite) in Khibina form a very thick (up to 1. 8 km.) cone sheet dipping inwardly at 25^{o} - 30^{o}, while in Lovosero they occur only as small bands and schlieren in the nepheline syenite series.

The minor alkalic intrusions in the Kola Peninsula may be speculatively considered to be disposed along four east-west belts. Altogether thirteen such intrusions have been recorded, as far as I know, but I have been unable to obtain descriptions of four of them (Afanasiev, 1939; Bobrievich et al, 1959; Borodin, 1957, 1958). On the map (fig. 1) these intrusions are represented by numbered points.

Following is a rapid survey of these complexes taken in their numerical order:

Belt I.

1. Chagve-Uaiv. In plan this intrusion is oval shaped, 1. 5 km by 1 km, consisting of a steeply dipping layered complex, probably a stromoconolith. According to Polkanov (1938) three intrusive phases can be distinguished: 1) albite-aegirine granosyenite, 2) quartz nordmarkite and albitized nordmarkite, 3) pegmatite and quartz veins. The most striking features of these rocks are, first the well marked banded structure, and secondly, the widespread alkali-metasomatism shown as albitization of feldspars, amphibolization of pyroxenes and carbonatization of all minerals. Although neither nepheline rocks as such nor carbonatites are present it is suggested that the banded complex was formed through the action of urtite or mariupolite-juvite magmas. Certainly in the light of later work on the Alnö rocks by Eckerman (1948) it is quite feasible that the banded granosyenites and nordmarkite are varieties of mobilized fenites.

Belt II.

2. Sebl-Yarvi (no information).

3. Gremyakha-Vyrmes. This igneous complex was most carefully surveyed and described by Polkanov and Eliseev (1941). In plan it is an elongated oval 20 km by 6 km., with its longer axis stretching N. N. W. -S. S. E. The country rocks are various types of Precambrian gneisses. All the intrusive rocks are characterized by a directional structure. The dip is very high and in places is vertical. Three intrusive phases are distinguished: 1) Ultrabasic-basic-intermediate phase which is subdivided into three separate series — A. Hortonolite peridotite, pyroxenite, gabbro, anorthorite; B. Peridotite, oligoclase gabbro, akerite, pulaskite; C. Syenite and pegmatite veins. 2) Jacupirangite, melteigite, ijolite, urtite series interbanded with nepheline syenite series (foyaite, juvite, malignite etc.). 3) granite-nordmarkite series. It is suggested that the jacupirangite-urtite series and the nepheline syenite series were formed from an alkalic residue, a product of crystallization — differentiation of the basic magma. This volatile-rich residue was probably also responsible for the pneumatolytic effects — autometasomatism of the igneous rocks, and allometasomatism of the country rocks. It is also suggested that the intensive allometasomatism led to the transformation of the country rocks into hybrid nepheline syenites.

Belt III.

The alkalic intrusions of this belt, often called Khabosero group of intrusions, were described generally by Kukharenko (1958) and Sergeev (1959).

4. Kovdozero (not to be confused with no. 12 Kovdorozero). This intrusive complex was described by Ivensen (no date), Zlatkind (1945, 1948) and Zlatkind and Shalilov (1946). It is a typical ring intrusion about 9 km in diameter with a perfect concentric structure. It is bordered by fenite developed in the surrounding gneiss-granite. The outer ring is made of jacupirangite, melteigite and ijolite, the middle — of melilite-bearing rocks, and the innermost part — of ultrabasic rocks. Bands and veins of carbonatites and pegmatites are very abundant, especially in the outer ring.

5. Afrikanda. This curious place name is said to have originated during the pioneering days of the geological survey. One of the geologists working there on a very hot summer day, exclaimed "What a hot day! A real Africa!" In plan it is a ring intrusion some 7 square km in area, but in its cross section it is more like an asymetrical funnel-shaped body with its axis inclined to the north. It was first described by Kupletsky (1936b, 1938a, 1938b) who discovered a knopite vein in the pyroxenite, then by Florovskaya (1939), Chirvinsky, Afanasiev and Ushakova (1940) Bagdasarov (1959) and Sergeev (1959). The country rocks are Precambrian biotite gneisses fenitised at the contact with the intrusion. The outer, incomplete, ring of a maximum width of 500 m consists of pyroxenites and melteigites. Towards the center the pyroxenites become, at first, fine grained and then change into coarse-grained ore-pyroxenites. These are characterized by an uneven distribution of the ore minerals and by the presence of schlieren and veins of titanomagnetite-knopite rock. The central part of the intrusion consists of an ore-olivinite eruptive breccia cemented by a coarse grained pyroxenite and vibetoite. All these rocks are cut by abundant veins of nepheline pegmatite of which three varieties are distinguished: knopite-schorlomite-nepheline and, pyroxene-nepheline. Carbonatite veins are also abundant. Kukharenko (1958) postulates three intrusive stages: intrusion of 1) olivinites 2)

fragmentation of olivinites and intrusion of pyroxenites, 3) intrusion of a carbonate alkaline magma produced by the diffusion of the alkali in the crystallizing pyroxenite magma. Such a magma gave rise to nepheline pyroxenites, nepheline pegmatites, melteigites and carbonatites.

6. Ozernaya Varaka. This intrusion was discovered in 1935 and described by Afanasiev (1939a) and Sergeev (1959). It is a small intrusion, in an area of about 1 square km. The country rocks are biotite-oligoclase gneiss, garnet-amphibole gneiss and schistose amphibolite. The exocontact fenitized zone varies in width from 10 m to 600 m. The peripheral zone of the intrusion consists of an urtite-ijolite-melteigite series which grades into alkali pyroxenites toward the center. Veins of carbonatites, nepheline syenites and cancrinite syenites are abundant.

7. Lesnaya Varaka. According to Afanasiev (1939b) this intrusion is about 20 square km in area. The outer zone consists of pyroxenite and pyroxene-feldspar rocks grading into olivinites and ore olivinites in the center. A small amount of nepheline pegmatite is present.

8. Salmagorsk (no information).

9. Pesochy (no information).

Belt IV.

10. Kuolo-Yarvi (no information).

11. Vuori-Yarvi. This intrusive complex, as described by Volotovskaya (1958), in plan is oval, 6 km by 3 km in size. Four intrusive phases are distinguished: 1) ultrabasic phase represented by olivinite, peridotite, pyroxenite and mica pyroxenite, 2) alkaline phase represented by ijolite, ijolite-melteigite, melteigite and rather rare jacupirangite and malignite, 3) ore phase represented by vein rocks composed of magnetite, forsterite, apatite and calcite, 4) carbonatite vein phase. The country rocks, such as gneiss, are strongly fenitised.

12. Kovdorozero. An intrusive complex, described by Koshitz (1934), made by alkalic syenite, ijolite and carbonatites.

13. Turyi Peninsula. This magmatic complex, discovered in 1905 by E. S. Fedorov, was described by Kranck (1928) and by Belyankin and Vlodavetz (1932). It is rather confusing that this place name provided two etymologically similar rock names applied to two different rock types, namely turjite (calcite-analcite-melanite biotite) given by Belyankin in 1917, and turjaite (nepheline-biotite melilitite) given by Ramsay in 1921. Unlike the other Kola Peninsula alkalic complexes, this magmatic complex consists of a set of dikes penetrating sandstones and quartzites. The rocks are highly heterogeneous, banded and striped. According to Belyankin and Vlodavetz three intrusive phases can be distinguished: 1) Monchiquite, alnoite, calcitized eruptive breccia, carbonatite. 2) Ijolite, turjaite, turjite, aegirine syenite, carbonatite. 3) Monchiquite, alnoite, augitite, nephelinite, carbonatite.

According to Kranck the primary magma of the Turyi complex was of an ijolitic composition, which through crystallization-differentiation first gave rise to the urtite-pyroxenite series and then to a succession of syenitic rocks, finally terminating with the formation of a residual liquid rich in alkalies, water and carbon dioxide.

"As is shown by the description of the rocks", writes Kranck, "a late crystallization of calcite almost always occurs, showing that an enrichment in lime has also taken place in the hydrothermal residual liquids. The calcite appears in a way which makes it probable that its compounds were contained in the primary magma."

Belyankin and Vlodavetz agree with this conclusion, thus "finally it seems that CO_2 in its major part, like F, S, P_2O_5 etc., is derived from the same primary magmatic source, as in the case of the silicate components of the Turyi eruptive rocks, and what has been said about CO_2 applies equally to H_2O of the Turyi dike complex."

In contrast to carbonatites, which these authors, regard as of pure magmatic descent. "The syenitic rocks of Turyi in our view, are just the products of the interaction of the ijolite magma (i. e. of the ijolitic magmatic phase) with the sandstones. Indeed, one can observe all the continuous mineralogical and space transitions from the syenites, on both sides, either to the ijolites, or to those contact sandstones, which, as described above, are particularly well represented in the region where ijolites are largely developed."

This completes the survey of the Kola Peninsula alkalic intrusions.

In size these intrusions vary from very large, like that of Khibina Tundras, to smallish plugs or dike complexes. In cross section they are circular or elliptical. The majority of them are comparatively small diatremes or explosion pipes, but the larger ones are confocal-concentric cycloliths and are of the nature of stromoconoliths in their upper parts, and ring dike complexes in their deeper parts. A very important feature of these magmatic complexes is the directional structure of the rocks varying from linear or planar structure of minerals to coarse banding, streaking and lamination.

The rocks entering into the composition of these igneous complexes, as shown by the examples from the Kola Peninsula, as well as those elsewhere, can be grouped into four principal groups or series which are:

I. Ultrabasic-basic-intermediate series mainly belonging to the alkalic variety, namely those containing small amounts of nepheline, analcite or other foids.

II. Peralkalic urtite-jacupirangite series.

III. Syenites and nepheline syenites.

IV. Carbonatites.

The rock types belonging to each of these groups are commonly found to pass into one another by means of a perfect gradation, whereas the assemblages of each group, while also showing gradational passage, can also exhibit cross cutting intrusive sequences. An important feature of these groups is that, while in the majority of cases the intrusive sequence is that shown by the order I, II, III and IV, other sequences are also commonly found. Thus one can find ijolite, nepheline syenite and carbonatite forming a banded complex in which the bands gradationally pass one into the other, and at the same time this banded complex consisting of the types belonging to groups I, II, III and IV may be cut first by carbonatite veins and then by monchiquite dikes.

Several interesting problems have emerged in the latest publications on the alkalic magmatic complexes in the Kola Peninsula. Thus Kukharenko (1958) discusses three important problems — the nature of the magma and the diversification of the igneous rock types, the problem of geochemistry and the classification of the ore deposits found in these complexes. According to this author the dominant magma involved in these complexes can be represented by a series varying from olivine and pyroxene rich fractions through melteigite and ijolite to urtite, often accompanied by nepheline syenites and later carbonatites. Geochemically these complexes combine the elements associated with ultrabasic and basic magmas, such as Mg, Fe, Ti, V, Ni and Cr, with the elements associated with SiO_2-rich magmas, such as Nb, Ta, RE, Y, Be, Sc, Zr, Hf, Th and U. The ore deposits occurring in these complexes are classified as follows:

Class I: Magmatic.

1. True magmatic: characterized by dispersed sideronitic or banded ores of iron and titanium, such as titanomagnetite and knopite.

2. Fusive: schlieren or veins of knopite-titanomagnetite ores.

3. Pegmatitic: found in nepheline syenites and pegmatites.

Class II: Postmagmatic.

4. Autometasomatic, due to the action of the solutions and emanations.

5. Pneumatolytic-hydrothermal.

6. Hydrothermal, such as rare minerals occurring in carbonatites.

Another important problem, that of fenitization, is discussed by Sergeev (1959). The country rocks of the Kola Peninsula magmatic complexes are various gneisses and schists, and the width of the fenite exocontact zone varies from 10 m to 600 m. Fenites are the quartzless albite-pyroxene rocks produced by the action of magmatic emanations. The following stages of fenitization are distinguished: 1) Preliminary stage — marked by the albitization of feldspar and amphibolitization of pyroxene. 2) Early stage — crystallization of albite and clinopyroxene. 3) Middle stage — intensification of the same process. 4) Final stage — complete transformation of the original rock into an aggregate of albite, anorthoclase and alkalic pyroxene. 5) Postmagmatic stage — leaching and deposition by the action of solutions, formation of carbonates and zeolites.

In certain cases the additive metamorphism may result in the transformation of fenites into rheomorphic syenites. The order of migration of separate elements into the exocontact zone is, in the case of intrusive olivinites and pyroxenites, (Na + Al), Mg (Na + Fe), Na, Ca, K, Fe, P, RE, Ti, Nb, and in the case of melteigite and ijolite (Na + Al), (Na + Fe), Na, Mg, Ca, P, RE, K, Fe, Ti, U, Nb.

The last problem, discussed by Petersilie (1958), is concerned with the unexpected discovery that in the Khibina magmatic complex appreciably large quantities of hydrogen, methane and other hydrocarbons are found in the ijolite-urtite series of rocks. As the amount of these gases in the country rocks is negligible, the author suggests that they are of magmatic derivation. Bitumens varying from petroleum to asphalt have been found by Bezkrovny (1958) in the kimberlite pipes in Siberia. Thus it is clear that hydrocarbons may be present in the ultrabasic magmas and that these hydrocarbons may not only act as agents in the crystallization or differentiation of magma, but also as sources of the carbon dioxide, so abundant in certain types of ultrabasic magma.

The work on the "alkalic ultrabasic rocks associated with carbonatites" in the U. S. S. R. has recently been augmented by numerous discoveries of these types of igneous complexes in Siberia. These complexes have been discovered in two regions of Siberia — Meimecha-

Kotui region (roughly 70°N., 105°E.) and Tuva region (roughly 52°N., 95°E.).

A new petrographic province has been discovered in the Meimecha-Kotui region of northern Siberia. Thus Moor and Sheinmann (1946) discovered a new rock type — a vitro-peridotite — which they named "meimechite" and a preliminary account of this new petrographical province was given by Sheinmann (1947, 1955), as well as by Moor (1957, 1959) and Moor and Zykov (1959). According to Sheinmann the north Siberian ultrabasic alkalic complexes occur in the form of plugs infilling explosion pipes traversing the Paleozoic deposits of the Siberian platform. Their age is probably the same as that of the "Siberian traps", namely Permian-Triassic. The origin of these pipes is similar to that of the kimberlite pipes of Siberia, South Africa or Brazil. The rocks infilling the pipes, range from dunite and meimechite, kimberlite, alnoite, pyroxenite to ijolite, urtite and late carbonatites. The carbonatites are found only in complexes containing the whole series peridotite-urtite. They occur in the form of dikes and veins and are of a late genesis.

In contrast to the more familiar low-to-high-silica magmatic differentiation, the alkalic ultrabasic magma gives rise to "all the transition from peridotitic rocks to nepheline rocks and forms a continuous series. One must note, however, that the nepheline melt is much more mobile than the ultrabasic melt, and its behavior differs from it. Otherwise, it is difficult to explain the fact that alkalic masses often get separated and form independent bodies of rocks. In certain cases, when the erosional level is not deep enough, one encounters only such alkalic rocks, but as a rule their exposures are not extensive. Their resemblance to the large bodies of such rocks found in the Kola Peninsula, suggests that the Siberian intrusions are of the same origin." (Sheinmann, 1955, p. 150). In what follows the author points out a close association in space and time between these intrusions and the widespread extrusive and intrusive basalt and dolerites usually referred to as the "Siberian traps". So, according to Sheinmann, "a constant coexistence of ultrabasic-alkalic intrusions with the contemporary basalts suggests that these two magma types could not be quite independent and on the contrary suggests that they were derived from certain masses closely associated in space." The magmatic history of these two associated magma types, is visualized by Sheinmann as being due to deep tectonic fractures of the earth's crust, affecting different levels of the subcrustal substratum.

Moor (1957, 1959) and Moor and Zykov (1959) agree that the Siberian plateau basalts and the alkalic ultrabasic rocks are approximately of the same Permian-Triassic age and are probably derived from the same source. According to Moor (1957) besides plugs or stocks composed of peridotite, olivinite, melilite peridotite, melteigite, ijolite and alnoite, these are numerous kimberlite pipes in the region of the Vilni and Olekma rivers, which may be genetically connected with the lavas and tuffs of basalt, dolerite, nepheline basalt, augitite and limburgite.

The problem of the genetic relation between the "Siberian traps", the alkalic ultrabasic complexes and the kimberlite pipes is as yet not completely solved. A general account of the newly discovered Siberian kimberlite pipes, some of them diamond-bearing, is provided by Burov and Sobolev (1957) and Bobrievich et al (1959). The genetic relation of the kimberlites to the "Siberian traps" is discussed by Leontiev and Kadensky (1957) who are of the definite opinion that the kimberlites and the "traps" are not only of the same Triassic age but are both products of differentiation of a basic magma. At the same time Moor (1959) and Moor and Zykov (1959) are inclined to accept a genetic relation between the alkalic ultrabasic complexes and the kimberlites.

In the Tuva region the alkalic igneous rocks were discovered in 1945. Yashina (1957) described two groups of intrusions of Caledonian age. The first group, containing more abundant intrusions, comprises trachytoidal nepheline syenite, nepheline-feldspar, fregmatite and juvite. The second group comprises the urtite-ijolite series of rocks, with associated syenites and carbonatites. A new rock type, tuvinite (calcite urtite), is described. It is suggested that the rocks of the urtite-ijolite series are genetically related to the basic and ultrabasic rocks, while the syenites are related to granites. Kononova (1958) describes intrusive stocks made of a differentiated and metasomatic series comprising pyroxenite, melteigite, ijolite, schorlomite-ijolite, urtite, Kåsenite and tuvinite. It is concluded that the rocks of the urtite-ijolite series are truly magmatic, but that the garnet and carbonate-bearing rocks are of a metasomatic origin. The metasomatism was produced by the action of carbonate-rich residual solutions derived from the ultrabasic magma. "The origin of the carbonate solutions which caused the active calcium metasomatism in the Chinka and Dakhunu massifs, are related by us to the urtite-ijolite intrusions. This is testified by the following facts: the formation of the primary calcite during the late stage of crystallization of the urtite-ijolite rocks, the increase of the amount of calcium in the principal rocks — forming minerals (pyroxene, nepheline), the space relations of the processes of calcium metasomatism to the fractures, which originally served as avenues of the intrusions themselves."

Arising out of this exploratory work a very animated discussion started a few years ago, headed by a very important survey of the whole subject by Borodin (1957). In the beginning of

his article, Borodin writes:

"The study of the occurrences of carbonatites has now shown us that they are characterized by the following features: 1) Presence of an endogenic rock essentially carbonatite in composition, and possessing a definite paragenesis of the principal and secondary minerals, including those containing rare elements; 2) genetic and often space connection with the massifs of normal and alkalic rocks; 3) occurrence of carbonatites without any carbonate rocks (limestones, dolomites or others) among the country rocks; 4) manifestation of intensive metasomatic changes of the country rocks, sometimes forming concentric zones around the carbonatite core; and 5) their occurrence in the stable regions of the earth's crust (ancient platforms, shields)."

A world survey of carbonatite occurrences suggests to Borodin the following classification: 1) Independent development of carbonatites which form pillar-like bodies and ring dikes (Chilwa, Nyasaland; Sukulu, Uganda; Mbeya, Tanganyika, Isoka, N. Rhodesia). 2) Besides carbonatites there are present apatite-phlogopite-olivine rocks, which form a circular zone around the carbonatite core, and there are also present alkalic rocks of subordinate importance (Bukusu, Uganda). 3) Carbonatites are accompanied by a zone of alkalic rocks of an ijolite type (Fen, Norway; Napak, Uganda; Muambe, Mozambique). 4) Carbonatites are accompanied by a large amount of varied rocks, including pyroxenite (more rarely-olivinites), ijolite-melteigite and apatite-olivine-magnetite rocks. 5) The main rock is pyroxenite. The zone of nepheline-pyroxene rocks may be absent. Lenses of carbonatite occur in pyroxenites (Loolekop, Transvaal). 6) Only ultrabasic and alkalic rocks are present, with or without small amounts of carbonatite (Magnet Cove, U. S. A., Ozernaya Varaka, Kola; Odikhinch, Siberia).

These six types are presumed to form a continuous series, characterized by a progressive decrease in the amounts of carbonatites, and increases in the amount of silicate rocks. At the same time these six types mark also the gradually deepening erosion levels of the complexes in question.

The main character of this series, namely the close association of carbonatites with the alkalic ultrabasic rocks, Borodin explains as being due to the deep-seated differentiation of an ultrabasic primary magma enriched in H_2O and CO_2. The occurrence of these complexes as infilling of explosion pipes drilled in the cratogene, is explained by this very deep location of the magmatic reservoir and by the nature of the volatile-rich magma. The concentric zonality of these complexes, i. e. fenite, nepheline-pyroxene series of rocks, carbonatites of the central core; — all of this suggests successive phases or surges of intrusions, corresponding to the progressive changes in the differentiating magma. At the same time, Borodin is very anxious to emphasize that not all members of this series were formed by direct crystallization of a magma of a composition corresponding to a given rock. The reservation applies particularly to the nepheline-pyroxene series of rocks. As already postulated in a previous article (Borodin et al, 1956) Borodin is anxious to emphasize the important role played by the processes of metasomatism in the formation of these rocks. This aspect Borodin develops in a further article (1956). In this he carries his idea to the point of assuming that the post-magmatic processes of autometasomatism produces a wide spread of nephelinization and aegirinization of the pyroxenites, transforming them into melteigites and ijolites. In this process he assumes that up to 50 percent of the original pyroxene of the pyroxenite can be replaced by nepheline, garnet or mica. Parallel with these processes there takes place a calcium and magnesium metasomatism, leading to the formation of apatite, perovskite, melilite, phlogopite and garnet. The final stage of magnesium and calcium metasomatism manifests itself in the formation of phosphates and carbonates. In this way metasomatic agents transform the originally alkalic ultrabasic intrusion into a series of metasomatic products ranging from fenite to carbonatite.

The abundance of rare elements among carbonatites, suggests that these elements were concentrated in the metasomatizing solutions representing late magmatic solutions. "Thus it follows from the above, that under carbonatite we must include only those carbonatite rocks, the formation of which is linked with the processes of metasomatic alteration of the ultrabasic rocks, and above all with the process of nephelinization. Therefore in the evaluation of the potentiality of ultrabasic-alkalic provinces, in respect of the finding of carbonatite deposits, the most important criterion will be the presence of nepheline-pyroxene rocks of metasomatic origin, associated with pyroxenites and peridotites."

Both Butakova (1956, 1959) and Konomova (1957) on the basis of the study of the Siberian rocks, strongly support the hypothesis of autometasomatism as an important factor in petrogenesis. In opposition to the idea of (Borodin, Butakova and Kononova) of an extensive autometasomatism stands Serba (1959) with his assertion that carbonatites are related to the process of nephelinization. His main argument is that the volume of carbonatites may be very high in relation to the volume of the associated silicate rocks and this fact speaks against the autometasomatic hypothesis. Volotovskaya and Kukharenko (1959) are also very skeptical on this subject of all-embracing metasomatism and believe in the independent existence of a melteigite-ijolite magma. Egorov and Surina

(1958), who have described chilled selvages of jacupirangite-melteigite against country rocks and associated carbonatite intrusive, into sedimentary rocks, are also most critical of this hypothesis. Egorov (1957, 1960) agrees with Borodin on the importance of metasomatism, but he does not agree that the nepheline-bearing igneous rocks and carbonatites are entirely metasomatic formations. He writes; "one must accept the reasonableness of Borodin's contentions, namely, about the vast scale of the phenomena of nephelinization in the complex alkalic-ultrabasic massifs. At the same time it is impossible to agree with his assertion that nephelinization leads to the formation, in the ijolites-melteigites, with a hypidiomorphic structure. Ijolites-melteigites, in their genetic aspect, represent not the result but the cause of the nephelinitization of the pyroxenites (a view, strange to relate, accepted in a way by Borodin). Nephelinitization must be relegated to the case of manifestation of metasomatism during the magmatic stage. In this respect it must be compared with the well-studied process of fenitization of country rocks of granitic composition. The two processes seem to be of an identical nature." According to Egorov carbonatites "are apparently the same kind of intrusions as the intrusions of pyroxenites or ijolite-melteigite. Apparently in the process of their formation, carbonatites pass through a longer stage of pneumatolytic and hydrothermal development, getting enriched in rare elements and passing through a series of other mineral and structural-textural changes." (p. 109).

It is obvious that Egorov does not doubt that carbonatites can be classed as exclusively magmatic as opposed to hydrothermal products. For him, late-magmatic to hydrothermal, is a more reasonable statement. In this he probably agrees with Dmitriev (1959) who described various carbonate rocks of metasomatic - hydrothermal origin in a volcanic pipe of Mount Chavida in Siberia.

PART II. INTERPRETATIVE PART.

Part I comprised a brief account of a) the recent work done in the U. S. S. R. on the alkalic ultrabasic rocks and carbonatites, and b) the discussions generated by such work relative to the processes involved. Part II is an attempt to provide an interpretation of the whole process of petrogenesis of this group of rocks. Fundamental to such discussion is certainly the voluminous literature published on this subject, such as the classical works of Brögger (1921) and Eckermann (1948), together with other publications by Polansky (1949), Pecora (1956), Campbell Smith (1956) and King and Sutherland (1960). My own studies of certain magmatic complexes, such as Fen in Norway and Alnö in Sweden, also form a very important feature of this background.

This attempt to outline a petrogenetic scheme for the group of rocks under discussion is based on the assumed factors involved in the diversification of igneous rocks in general. In my opinion much confusion is created in petrology by the universalization of one particular factor and the complete denial of other factors. I have already proposed in brief (Tomkeieff, 1954) that the diversification of igneous rocks may be due to the following factors: 1) Selective remelting of the material of the earth's crust, 2) tectonogenesis, 3) diffusion-differentiation of the magma prior to crystallization, 4) crystallization-differentiation, 5) autometamorphism, and 6) hybridism.

At the same time I emphasized that in the "large scale" study of rocks as, for example, in petrochemistry, it must also involve the "small scale" study, as in the science of leptology (the science of fine structure of matter). The six principal factors of magmatic petrogenesis play varied parts in the formation of a given assemblage of rocks. In the present case, namely alkalic ultrabasic rocks and carbonatites, their role may be outlined as follows:

1. The selective remelting of the gravity differentiated earth's crust which probably occurred in the lower part of the basaltic and the upper part of the peridotitic zones. In the case of abundant eruption of rocks of syenitic composition, like that of the Oslo district and the Khibina and Lovozero massifs the intermediate zone must be involved by a remelting.

2. The majority of these igneous massifs occur as cycloliths varying from an explosion pipe to a large ring dike complex or dome. Probably all types of cycloliths are due to the explosive nature of a volatile rich magma underlying kratogenic regions.

3. In my opinion diffusion-differentiation played a very important part in the formation of the rocks in question and so this type of magmatic differentiation is discussed here; the other three principal factors, below.

In 1890 Rosenbusch outlined his "kern" hypothesis, according to which the main lines of the diversification of igneous rocks were determined by the formation of partial magmas, each of them tending towards a stochiometric composition. This was due to the formation, in the still liquid magma of atomic groups or nuclei (kern). Thus, excluding oxygen, the kern of fayalitic magma was (Na, K) $AlSi_2$ and that of the granitic magma characterized by a higher number of silicon atoms. This hypothesis, vaguely anticipating the modern theory of silicate structure was welcomed by only a few contemporary petrologists, e.g. Loewinson-Lessing, who, in his work on theoretical petrology (1899), postulated that prior to crystallization the magma already contained groups of

atoms, as a kind of complex molecular or proto-mineral structure, fore-shadowing the principal cyrstalline minerals which were formed on cooling. These molecules can, under certain conditions, migrate or diffuse in the magma prior to its crystallization. This hypothesis was maintained by Loewinson-Lessing in his later works (1933). Diffusion-differentiation of alkalies and volatiles, as a factor in the formation of alkalic rocks, was clearly formulated by Smyth (1913, 1927). Magmatic diffusion, especially where combined with crystallization-differentiation, thus leads to what Scheumann (1922) calls the "fusive" and the "accumulative" phases of the magma. Fersman (1935) is particularly emphatic on the importance of the pre-crystallization grouping of cations and anions as influencing the subsequent order of crystallization. Ionic dissociation, molecular groupings and diffusion are also discussed by Bilibin (1939, 1940) who writes "In deep magmatic hearths where magma, prior to the beginning of its crystallization, is at a very high temperature, there undoubtedly occurs a dissociation of molecules. It is on the cooling of the marginal parts of the hearth that there may be found the beginning of an association of certain definite molecules. Because of this, the homogeneity of the magma is disturbed and, following the principle of Soret, there must occur a diffusion of the associated molecules inside the hearth and of the dissociated parts of the same molecules towards the periphery (Bilibin, 1939, p. 783). This must be a variable diffusion, because elements of a low ionic potential, like the alkalies and volatiles are by nature more mobile and these will accumulate in the fusive phase of the magma. The association of alkalies with volatiles is often misunderstood. Alkalic rocks are usually rich in volatiles, but "from this it is concluded that the composition of such magmas is the result of their being rich in volatile components, while the reality is just the reverse, viz, the richness in volatiles in certain alkalic magmas is the consequence of their composition, corresponding to the later stages of differentiation". (Bilibin, 1940, p. 228). Wahl (1946) also invokes the Soret effect — the diffusion of certain molecules towards the chilled part of the magma — as responsible for the themal diffusion and as a possible cause of magmatic differentiation, and he concludes that "from the above review of the present knowledge of thermodiffusion, both experimental and theoretical, it is evident that the modification has great power to bring about inhomogeneity in previously homogeneous liquids and molten masses, many of huge size, with which we are concerned in rock magmas." Saether (1950) in his application of the principle of diffusion-differentiation to the formation of the alkalic rocks, invokes the effect of the upward migration of CO_2, H_2O, F, Cl contained with alkali cations. Sundius (1957) supports the same thesis and particularly emphasizes the role of alkali carbonates and migrating substances. Shcherbina (1953) reminds us that it was Faraday who in 1934 proved the presence of an electrolytic dissociation in the silicate melts and that one must postulate magma containing simple cations and anions and complex anions of the type $(Al\ Si_3O_8)^{1-}$, $(TiSi_4O_{12})^{4-}$ and so on. Vlasov (1958, 1956) also supports the hypothesis of diffusion-differentiation, which he calls "the emanational process" which plays an important part combined with the crystallization-differentiation, especially in the formation of the alkalic rocks. Khitarov (1958), in his experiments on the effect of water on powdered basalt placed in an autoclave, found that the water-soluble extract, in terms of Na, K, Al and Si, at low pressure approaches nepheline syenite in composition, and at high pressure, quartz keratophyre. From these and other experiments he concluded, that "If during the stage of existence of magmatic liquid the role of volatiles is enormous in the redistribution of the matter through thermodiffusion, then, to an even greater extent the importance of volatiles is marked, particularly in the first instance, of water, during the process of crystallization. In this stage of the life of each melt, during which cooling produces a separation of a certain amount of a solid phase, water, enriching the residual liquid, also greatly increases its mobility and in this way not only assists differentiation, but also acts as one of the fundamental regulators of this process." Korzhinsky (1950, 1957), a great authority on metamorphic processes, discusses the relative mobilities of cations and anions involved in the high-temperature metasomatic processes. He postulates a stream of "through-magmatic solutions" affecting the course of the formation of minerals in the magma and producing later post-magmatic metasomatism. One of the effects of such a metasomatism is the formation of carbonatites, which are often associated with the nepheline syenites.

Thus, we see that at the present time there are a number of scientific workers who consider that ionic migration does occur in magmas and that such a differential migration could lead to the diffusion-differentiation of magma. Whether such a mobility is conditioned by the size of the ions, these being determined in crystalline edifices by the relative strength of the chemical bonds or as postulated by Szádeczky-Kardoss (1954, 1960), by the relative ionic densities (ionic weight divided by ionic volume) of the ions involved, it is impossible to say.

Passing now to the concrete examples of complexes of alkalic ultrabasic rocks and carbonatites, both of these are found in the U. S. S. R., and described in the first part of this article, and other similar occurrences in Europe, Africa and elsewhere, it is important once more to state that these complexes are made of four distinct rock series, occurring singly or together in the various complexes. These rock series, are:

1. Normal series of calc-alkali or alkalic rocks, which may range from ultrabasic to basic and sometimes to intermediate rocks. Often represented by peridotites, pyroxenites, feldspathoidal basalts and trachy-basalts.

2. Peralkalic series varying from jacupirangite (alkaline-ore pyroxenite) to ijolite, melteigite and urtite (pyroxene-nephelinolith).

3. Alkalic and nepheline syenites of a great variety of types, passing into nephelinized granite (fenite).

4. Carbonatites of calcium, magnesium and iron (the last ones usually oxidized and altered to a red iron ore).

In my opinion the four rock series outlined above can be linked up into one petrogenetic scheme. Such a scheme, although a hypothetical one, seems to me to agree best with the accumulated facts. Here is a brief summary of this petrogenetic scheme. Let us assume that the primary magma belongs to the world's abundant mildly alkalic magma type (1st series), that of the peridotite-olivinite-basalt-trachybasalt series. Within these series let us take a peridotite magma rich in hyperfusible constituents. This magma, as affected by a combined crystallization and diffusion differentiation, will, under kratogene conditions, give rise to an alkali-rich fusive phase. This may move away as an independent per-alkalic magma which, on cooling and further crystallization and diffusion differentiation, is capable of forming the jacupirangite-urtite series of rocks (2nd series). At the same time this magma type, still developing its fusive phase, will produce a highly fluid residual liquid which, at high temperatures, will contain alkalies as alkali carbonates. With the temperature falling, say below 500°C, the alkali carbonates, acting on already crystallized silicates and on silicate molecules still in the melt, will exchange their alkali cations for Ca, Mg and Fe cations. Such an exchange, involving a simultaneous production of nepheline and $R''CO_3$ molecules, will lead to two complementary autometasomatic and hetero-metasomatic processes, nephelinization and carbonatization. These two processes will give rise to the following series of rocks. 1) fenite-mobilized fenite-hydrid nepheline syenite (3rd series) and 2) carbonatites (4th series). Diagramatically this process can be represented this way:

Peridotite → jacupirangite urtite series ↗ nepheline-syenite-fenite-granite-(country rocks)
↘ carbonatites.

Let us now discuss certain details of this scheme. The first contention is that the peralkalic series is derived from the alkalic series by means of diffusion of alkalies and volatiles. It is assumed that the cations Na^+ and K^+, separately or in combination with various anions such as Cl^-, F^-, OH^-, SiO_4^{4-}, CO_3^{2-} or HCO_3^- migrate to the upper region of the magma reservoir, alkalizing the upper magmatic zone and at the same time de-alkalizing the lower zone. In my work on the petrochemistry of the Scottish Carboniferous-Permian igneous province (Tomkeieff, 1937) on the basis of 300 chemical analyses, I produced a diagram illustrating such a diffusion differentiation, a diagram which is reproduced here (fig. 2). Here it is assumed that it was the principal magma of the B-series, namely the olivine-basalt magma, which was affected by the diffusion-differentiation and which gave rise to the peralkalic teschenite magma and the complementary de-alkalinized quartz-dolerite magma. The development lines of these three series A, B and C indicate the trend of differentiation, probably controlled mainly by the sequence of crystallization in each of the three magmas in question. In another paper (Tomkeieff, 1949) I published a similar diagram (fig. 3) relating to the igneous rocks of Kamchatka and Japan.

Of the complexes described in the first part of this paper, the Gremyakha-Vyrmes complex has a well developed normal series of rocks (ultrabasic to intermediate). The development line of this series, placed together with the development line of the jacupirangite-urtite series belonging to the same complex, suggests that, by analogy with the Scottish, and Kamchatka examples, one may invoke diffusion-differentiation as a factor operating on the primary magma of this complex. The trend of emanations is indicated conjecturally by arrows on the diagram (fig. 4) but actually one could postulate a pyroxenite magma belonging to the normal series becoming enriched in the alkalies. Such a magma, in composition near to melteigite, may through a combined action of crystallization and of diffusion-differentiation, produce a fusive phase corresponding to ijolite and urtite, and an accumulative phase corresponding to jacupirangite. In this way one can imagine the genesis of the peralkalic magma, rich in alkalies and volatiles and consequently very fluid and chemically most active and carrying a great amount of metasomatizing agents. This peralkalic magma, when intruded in a country rock of granitic composition will, no doubt, transform it, first to fenite, then by stages to more and more nephelinized fenite, which at a certain stage will become mobile or form a hybrid between granite and, let us say, nephelinolith (urtite) or any other phase of the pyroxene-nepheline magma. According to Eckermann (1950) in the Alnö complex nephelinization is a concluding stage of fenitization and its final product is a rheomorphic (liquefied) fenite. Strauss and Truter (1951) also agree that certain fenites may be "mobilized" and intrusive, and that they do represent "the ultimate stage of fenitization," and also that "there can be no doubt that the outer zones of alkalic

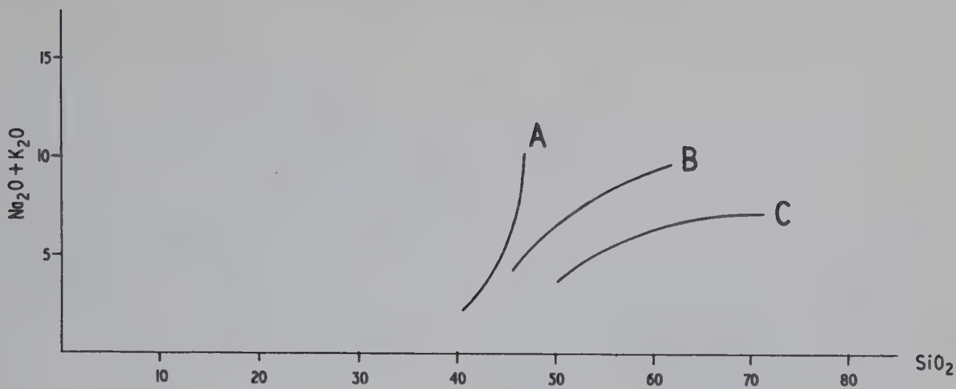

FIGURE 2. Scottish Carboniferous-Permian igneous rocks assemblage plotted on an alkali/silica diagram:

A. Peralkaline series (picrite-teschenite-lugarite)
B. Basic to intermediate series (olivine-basalt-trachybasalt-trachyandesite-trachyte)
C. Subalkalic series (quartz dolerite-felsite).
(Tomkeieff, 1937)

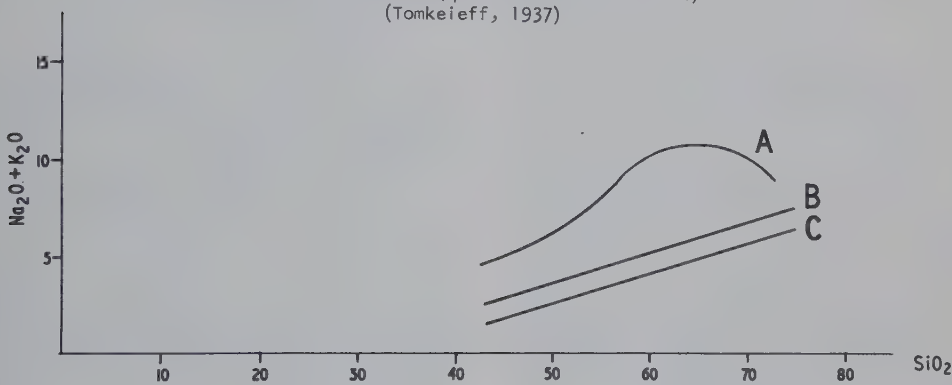

FIGURE 3. Japan-Kamchatka igneous rock assemblage plotted on an alkali/silica diagram:

A. Alkalic series - B. Basalt - andesite series - C. Subalkalic series
(Tomkeieff, 1949)

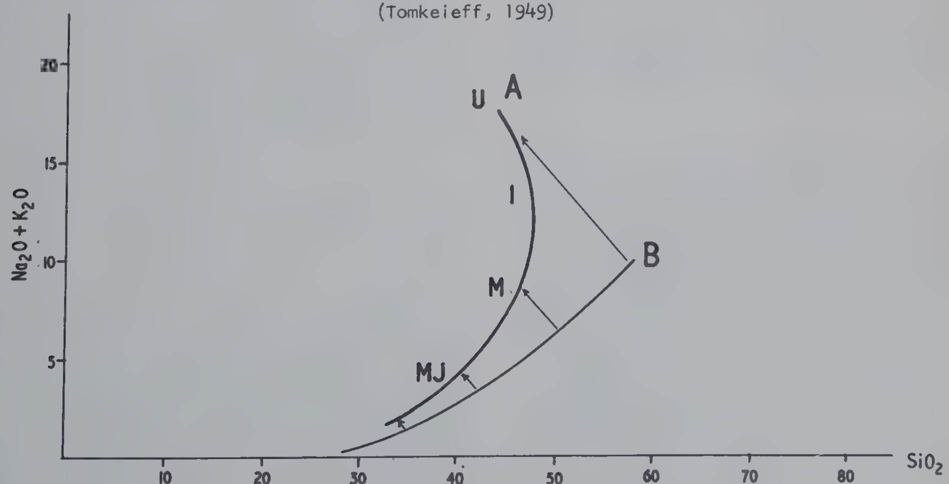

FIGURE 4. The rocks of the Gremyakha-Vyrmes complex plotted on an alkali/silica diagram:

A. Peralkalic series (U - urtite, M - melteigite, M.J. - melteigite-jacupirangite)
B. Ultrabasic - basic - intermediate series

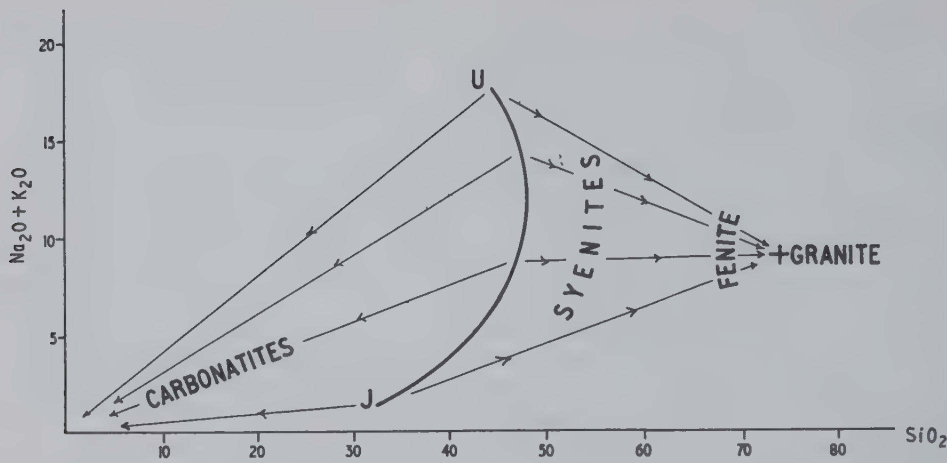

FIGURE 5. Diagrammatic representation on the alkali/silica diagram of the petrogenetic process of formation, from the urtite-jacupirangite magma, on the one side of the (1) syenites-fenite metasomatites, and the other of the (2) carbonatites. Pure carbonatites are located at the zero point of the diagram, while the average granite is marked by a cross.

granite, umptekite and pulaskite are fenites formed by the introduction of material from the alkalic center" (p. 119).

Thus I assume that the numerous varieties of alkalic syenites, such as khibinite, rischorite, juvite, malignite and others, usually present in the alkalic ultrabasites-carbonatites complexes, are hybrids produced by alkalic metasomatic fluids derived from the jacupirangite-urtite magma on the granitic country rocks. In Figure 5 the development line of the peralkalic magma, extended to jacupirangite, is shown by means of arrows to line up with the field of granite. This metasomatic process, principally manifest as nephelinization, produces first fenite and then, or mobilization fenite, many varieties of alkalic syenites, which are either interbanded with the rocks of the jacupirangite-urtite series or with the carbonatites, or exhibit cross-cutting relations, showing the relative independence of this hybrid magma.

In the case of the Gremyakha-Vyrmes complex one is forced to postulate a close space and time relationship between the normal ultrabasic-basic-intermediate magma and the peralkalic magma, but in a number of other complexes, such as Fen and Alnö, the main bulk of the normal magma is left in depth and the only active magma is the peralkalic magma. In other cases, such as large intrusive bodies of syenites of the type of Oslo district, Khibina and Lovozero Tundras, one must postulate a deep-seated diffusion-differentiation producing a large melt zone of an alkali-rich magma belonging to the intermediate layer of the earth's crust. In these cases the peralkalic magma plays but a subordinate role in the eruptive sequence. The ultrabasites themselves may be classified as:

1. Cratogene alkalic ultra-basites-kimberlite, alnoite, damkjernite, alkalic peridotite, alkalic pyroxenite and melilite-bearing rocks, found mainly in diatremes.

2. Orogene subalkalic ultrabasites-serpentinites, ophiolites, sill-like intrusions in folded strata.

It is the cratogene ultrabasites, the magma of which is alkali and volatile rich, that are apt to generate the peralkalic jacupirangite-urtite magma. This magma is often very rich not only in alkalies, but also in carbon dioxide. Thus, in all probability, the alkalies are present in the magma as alkali carbonates and alkali bicarbonates, Na_2CO_3, K_2CO_3, $NaHCO_3$, $KHCO_3$ as well as numerous hydrous carbonates. Such are probably the molecules present in the peralkalic magma and in its emanations which are responsible for the metasomatic effects, both auto- and hetero-metasomatism. One therefore postulates that alkali metasomatism, so common in magmatic processes is mainly due to the action of alkali carbonates which, like many other alkali compounds, are very soluble and form individual minerals only in exceptional cases where there is a prevailing environment of volcanic emanations or volcanic evaporites. The role played by alkali carbonates in the magma is shown by numerous examples of the occurrence of such minerals as trona, thermonatrite, natron and gaylussite among volcanic ashes and evaporites derived from lakes fed by volcanic thermal springs. These are magnificently shown by many African examples, such as the Pretoria salt pan, Lake Magadi in Kenya, Lake Natron in Tanganyika and the volcano Ol Doinyo Lengai situated to the south of Lake Natron — a volcano which erupts ashes loaded with trona. Alkali carbonates frequently occur in volcanic sublimates and

dissolved in the volcanic thermal springs. Carbon compounds are very important components of volcanic gases. Alkali silicates, such as sodium metasilicate Na_2SiO_3 or waterglass and other soluble compounds are also abundant in volcanic springs. In contrast to the highly soluble alkali carbonates and alkali silicates we have the less soluble carbonates and silicates of alkaline earths and iron (Ca, Mg, Fe) and especially the alkalic-aluminum silicates, such as the feldspars and the feldspathoids.

Beginning with V. M. Goldschmidt's classical work on the four component system

$$CaCO_3 + SiO_2 \rightleftharpoons Ca\,SiO_3 + CO_2$$

and carried on by numerous other investigators, the latest being, Wyllie and Tuttle (1960), we know that $CaSiO_3 + CO_2$ are really stable at temperatures above 750°C and $CaCO_3 + SiO_2$ are really stable at temperatures below 500°C, but, on the other hand, it is clear from the TP equilibrium diagram that at temperatures as low as 750°C systems containing $CaCO_3$, Na_2CO_3 and K_2CO_3 can exist under high pressures. Wyllie and Tuttle, who have studied the system $CaO - CO_2 - H_2O$, consider that the "carbonatite liquid" containing up to 13 percent H_2O can be produced at 685°C at 1000 bars pressure. Such a liquid, according to them, may stand for a simplified carbonatite magma. In my opinion carbonatite high temperature magma does not exist because alkali carbonates at high temperature are more stable than lime or magnesium carbonates, and because on cooling below the critical point of solvent water, say 400°C and 217 atmospheres pressure, the equilibrium is shifted from Na_2CO_3 to $CaCO_3$, or $MgCO_3$ or $FeCO_3$. In other words sodium carbonate present in the magma reacts with calcium, magnesium or iron silicates either present in the already crystallized minerals or in the "shadow mineral" molecules present in the liquid magma. One may thus postulate various reactions occurring in the magma, such as the sodium carbonate reacting, with the anorthite molecule to produce a nepheline molecule and calcite, as follows:

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + Na_2CO_3 = \underset{\text{nepheline}}{2NaAlSiO_4} + \underset{\text{calcite}}{CaCO_3}$$

This reaction equation, as one of those possible in the process of autometasomatism or heterometasomatism, may be considered to be a most significant reaction, for it indicates the possibility of two simultaneous and complementary processes taking place during the cooling of the magma, the two complementary processes being those of nephelinization and carbonatization. So we have the anorthite molecule, an important ingredient of a basic magma attacked by sodium carbonate and so giving rise to nepheline and calcite in the following way

$$\text{Anorthite} + \text{sodium carbonate} \begin{array}{l} \nearrow \text{nepheline} \\ \searrow \text{calcite} \end{array}$$

This reaction, in a way, is similar to that of the transformation of serpentinite into talc-carbonate rocks:

$$2H_4Mg_3\,Si_2O_9 + 3CO_2 =$$
$$= H_2Mg_3\,Si_4O_{12} + 3Mg\,CO_3 + 3H_2O$$

In both cases the formation of carbonates of divalent cations is due to the exchange reaction between the silicate and the carbonate phases. In the case of alkali carbonates giving rise to nepheline and calcite this exchange reaction is entirely determined by the concentration of alkali carbonates in the peralkalic magma. This means that there is no such thing as a "carbonatite magma" but only "magmatic carbonate", a precipitation product of alkali-alkaline earth exchange reaction. The carriers are alkali carbonates but the depository products are alkaline earth carbonates, formed mainly during the hydrothermal stage when the solutions of monovalent cations became unstable in the presence of newly forming divalent cations. In this way one can reconcile the ideas of Brögger and the idea of Bowen on the subject of Fen carbonatites. There is no high-temperature "carbonatite magma" but only alkali carbonates present as solute in the high-temperature magma. On the other hand the alkali-earth carbonatites are generated from the alkali carbonates during the hydrothermal stage of the magmatic history (below 400° C). These carbonates are the product of a replacement reaction and thus products of a metasomatic-hydrothermal formation, showing towards earlier formed minerals both replacement relations and successive crystallization relations. The hydrothermal origin of carbonatites was the main contention held by Bowen (1924, 1926).

It is interesting to note the complementalness of nephelinization and carbonatization as shown by the reaction:

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + Na_2CO_3 = \underset{\text{nepheline}}{2NaAlSiO_4} + \underset{\text{calcite}}{CaCO_3}$$

Such an isochronic and complementary reaction no doubt explains the petrological features of many rocks encountered in the alkalic ultrabasic-carbonatite complexes and provides a guide for a new interpretation of recorded data. Certain nepheline-carbonate-bearing rocks illustrate fossilized reactions of replacement and neoformation, because both nepheline and calcite show these features. The whole is really dependent on the relative solubilities of the minerals in question: highly soluble alkali carbonates; less soluble carbonates of divalent bases, and highly insoluble alkali and alkaline-earth aluminum silicates. In this way leptology serves as a basis for the interpretative genetic petrology.

This petrogenetic scheme is roughly repre-

sented on the alkali/silica diagram (fig. 5) where the evolution of the peralkalic magma is shown by its development line stretching from jacupirangite to urtite, the hybrid syenite-fenite-granite series shown on the right of this line and carbonatite-silicate series on the left of the line.

Part of this scheme, as applied to the Fen district, I outlined in 1938 (Tomkeieff) but at that time I was unaware of the role of the alkali carbonates in the magmatic transport, both of alkalies and of carbonates. The present scheme provides unity and coherence to the interpretation of a number of alkalic-ultrabasic rock series associated with carbonatites and also provides a new interpretation of the origin of the carbonatites.

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AUTHOR'S NOTE

An important monograph has reached me too late for inclusion in the References and discussion in the text. It is:

Vlasov, K. A., Kuz'menko, M. V. and Es'kova, E. M., 1959, Lovozerskii shchelochnoi massiv. [LOVOZERO ALKALINE MASSIF]: Publ. Acad. Sci. U. S. S. R. --S. I. T.

ON THE TYPES OF METALLOGENIC PROVINCES AND ORE DISTRICTS[1,2]

by

Ye. A. Radkevich[3]

• *translated by Royer and Roger, Inc.* •

ABSTRACT

This paper discusses various aspects of the metallogenic classification of ore provinces and districts. The nature of the ores is related not only to the time of formation or the stage of geologic development with which they are associated, but also the geologic structure and the mineral composition of the rocks containing them.

In both ancient and young regions two types of development have been established: femic in zones of deep faults, and sialic in areas of subsidence. In all types of ore regions there are three principal categories of structure, which determine the positions of the ore zones – basins, uplifts and marginal faults. The metallogenic significance of these structural elements is different in regions of different natures.

The former metallogenic conception of the relationship between the nature of the mineralization and the time of its formation and its association with a given stage of geotectonic development must be supplemented by the new concept of the structural position of the ore-bearing zones: not only the time of the igneous activity, but also the structural disposition of the ore zones and their geologic history, determine their metallogenic features. Mineralizations of different types may develop at the same time in adjoining zones. --Royer and Roger, Inc.

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INTRODUCTION

Metallogeny is the science which studies the laws governing the distribution of ore deposits in the earth's crust; thus it has very far-reaching sources. The association between ore deposits and the major belts and zones of the earth was observed long ago. As early as 1749 Lomonosov noticed the similiarity between the copper ores of the Kurile Islands and those of Japan, explaining it by the fact that "Japan and Kamchatka lie upon a single crest, which is broken only by the sea and is manifested by the islands emerging from beneath the waters".

Approximately one hundred years ago I. A. Poletika (1866), considering the regularities in the disposition of gold-ore deposits, noted the enormous ore zones of Asia and America and determined that they were branches of a single ore belt which much later came to be called the Pacific Ocean ore belt. One branch of this belt, as I. A. Poletika pointed out, "follows the American shore of the Pacific Ocean through Bolivia, Peru, Colombia, Mexico and California; the other follows the Asiatic coast". On the other side of the Pacific Ocean, wrote this scientist, "stretches a line of gold deposits which is still more discontinuous, but is remarkable for its extraordinary length, for the variety of its gold-bearing ranges and the positions of the gold deposits in them, and is no less remarkable than the first line for the richness of certain of its parts."

This line begins with New Zealand and Australia, extends through the islands of Java, Sumatra, the Celebes and Borneo, and extends into China. The continuation of this enormous zone I. A. Poletika considers to be the vast ore belt which A. Ye. Fersman later called the Mongol-Okhotsk zone. Then, as I. A. Poletika writes, "follows the majestic line of the Siberian gold-bearing mountains; this occupies the entire southern part of Siberia, where it borders upon China, and stretches perpendicular to the shores of the Pacific Ocean from the Sea of Okhotsk along a line between 50° and 60° North latitude". Farther west, on the continuation of this same zone, are the gold-bearing regions of the Salair, Katun', and the Altay.

The laws governing the emplacement of ore deposits have also attracted the attention of other Russian geologists -- A. P. Karpinskiy (1881), I. V. Mushketov (1877), A. D. Ozerskiy

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[1]Translated from K voprosu o tipakh metallogenicheskikh provintsiy i rudnykh rayonov: pp.25-59, in Zakonomernosti razmeshcheniya poleznykh iskopayemikh[Regularities in the distribution of minerals], ed. by N.S. Shatskiy, v.2, Akademiya nauk SSSR, Otdelenie geologo-geograficheskikh nauk, Moskva, 1959.

[2]This article by Ye.A. Radkevich is of interest for its posing of a number of extremely important problems of metallogeny. It must be noted, however, that some of the author's views on tectonics, like the particular tectonic terms used by him, are not generally accepted. --Russian Editor.

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(1867) and I. S. Bogolyubskiy (1872); thus even in the first stages in the study of these ore territories a clear conception was formed of the parallel zonal distribution of the ore deposits of the Urals, the Transbaikal and other regions. Similar types of metallogenic generalizations were a consistent feature of the investigations of the geologic and mineral riches of these ore-bearing provinces. The name "metallogeny", as is known, derives from deLaunay (1892), who also drew some interesting conclusions in the field of metallogeny.

The determination of the empirical laws governing the emplacement of ore deposits was always accompanied by attempts to explain the causes lying behind these laws, which geologists sought in the peculiar features of the surrounding rocks, the manifestations of igneous activity and other geologic factors. The zonal distribution of the ore deposits was noted by A. Ye. Fersman (1926), V. A. Obruchev (1926), V. P. Nekhoroshev (1938), I. F. Grigor'yev (1934), S. S. Smirnov (1936) and others.

In more recent years metallogeny has become an independent area of scientific research or even an independent science - lying on the boundaries between regional geology, tectonics and the science of ore deposits. Particularly great achievements have been made in metallogeny in recent years in the USSR; this is not surprising in view of the fact that the systematic planning of scientific operations over great territories requires that prospecting work be supported by sound scientific principles, as well as that the extensive territory of the Soviet Union provides excellent material for a comparative analysis and for drawing generalizations regarding its metallogeny.

The general principles of metallogenic regionalization have been worked out by various authors. One of the first to set out upon these problems was V. A. Nikolayev (1944), who noted the peculiar features of the development of different structural-facies zones and, in particular, distinguished zones of positive (geanticlinal) and negative (geosynclinal) features, which are characterized by different geologic properties.

A systematic conception of the association between metallogeny and the peculiar features of the development of igneous complexes, which change regularly with time during the evolution of mobile zones, was elaborated by Yu. A. Bilibin (1955). The method of metallogenic analysis suggested by Yu. A. Bilibin and applied in distinguishing all the zones, regardless of their age, and principally in the major stages of development, makes it possible to compare metallogenic regions of different ages and to note the possible types of ore mineralization in relation to the complexes of sedimentary and igneous rocks developed in the particular region.

This type of analysis, which may be called comparative metallogenic analysis, was elaborated in VSEGEI (Serpukhov, 1955; Semenov, 1957; Serpukhov, Domarev et al.), provides the means of determining the general trend of development of metallogenic regions, and of the evolution of their igneous activity and mineralization in time. It can be used in constructing small-scale maps, in order to determine the changes in these general features of evolution and the overall trend of the development of the ore mineralization in association with igneous activity, tectonics and other geologic factors.

On the other hand, as applied to medium-scale and even more to large-scale maps and researches, as already noted in other papers (Satpayev, 1955; Radkevich, 1958), the method of comparative metallogenic analysis has certain deficiencies. These cases require more detailed analysis of local laws, a more specific and differential approach to the subdivision of igneous rocks and, in addition to their distinction according to stages of development, such other factors as the systems of faults and fractures, the details of folded structures, the alterations of the surrounding rocks and so forth. Large-scale metallogenic maps may be called maps of ore-controlling and ore-prospecting criteria. Their construction requires the use of specific methods specially worked out in the practice of mapping the locations of economic mineral deposits.

Thus, even at the present time there are different types of metallogenic investigations, each of which is associated with the scale of the map and with the purposes for which it is drawn.

But other methods, apart from the comparative metallogenic analysis of VSEGEI, may be used both in large-scale and in small-scale maps. In particular, one may draw maps reflecting ore districts with mineralizations of specific types and different ages, occupying different structural-tectonic positions and having different histories. Metallogenic maps of this nature still do not exist, and it is still too early to speak of the detailed methods of constructing them. This article will attempt to approach the problem of the possible types of ore districts, which may form the basis for metallogenic mapping.

The types of ore provinces are taken into account in constructing metallogenic maps by the method of Yu. A. Bilibin; in distinguishing the complexes of rocks that correspond to specific stages of development, the maps constructed according to this method also show complexes of ore deposits formed regularly in association with one sequence or another of igneous or sedimentary rocks, at a particular stage of development of the mobile zones, and which are significant for general forecasts of the occurrence of ore mineralization. But such

division into stages does not always completely meet the requirements of metallogenic analysis. For example, the metallogeny of regions of different ages, the relationship between the nature of the mineralization and the geochemical "profile" of the ore province and the local features of the structural-facies zones, their history, geologic structure and the lithologic composition of the various sequences in them are not sufficiently clearly reflected. Quite often deposits of the same age, but occurring at different structural facies zones, differ essentially in the nature of their mineralization.

As an example, we may cite the differences in mineralization between the Rudnyy Altay, which D. I. Gorzhevskiy believes to be association with a region of relative uplift and major faulting (zinc, lead), and the Kalba-Narym zone, which is associated with subsidence[4] (tin, tungsten). The same relationships may be observed in the case of the Transbaykal ore zones, which are close to each other in age; the polymetallic zone associated with the Priargun' uplift and the tin-tungsten zone associated with a prolonged subsidence. The fact that tin and tungsten are connected with areas of greatest subsidence and that lead and zinc are associated with uplifts has also been noted earlier in the literature (Radkevich, 1956; Gorzhevskiy and Kozerenko, 1956; Labazin, 1957 a and b, etc.). Nevertheless, this relationship is still not reflected on metallogenic maps. There are also other specific features of the structural position of certain types of deposits, such as the association between gold mineralization and the marginal faults and borders of platform structures.

These examples will show that in metallogenic analysis it is important to distinguish not only formations of different ages, but also structural-facies zones of various types, with which the different types of mineralization will be associated. This circumstance compels us to analyze the relationship between the nature of the mineralization and the types of structural-facies zones and to attempt a typization of the ore provinces and ore districts from this standpoint.

The question immediately arises: is it possible to distinguish general types of ore provinces, not to mention ore districts, which are extremely varied and would appear to be unique, at least in their detailed features? The examples of the Kalba, Transbaykal and Primor'ye regions cited above indicate that in spite of this variety of metallogenic regions, one may nevertheless distinguish certain general features and tendencies in the development of their mineralization.

A BRIEF REVIEW OF THE DIFFERENT TYPES OF ORE PROVINCES AND DISTRICTS.

Below we shall briefly characterize the different ore regions of the platform and geosynclinal types, in order to show the variety in the types of ore regions and the necessity for different approaches to their metallogenic analysis, as well as to point out a definite repitition of certain of their features which may be used as a basis for distinguishing types of ore-bearing regions and districts.

Regions of the platform type show no less variety in their metallogeny than do folded zones. This variety is partly due to the different degrees of their erosion and covering with a mantle of sedimentary deposits. For example, the southern shields – the South American, African and Australian – have considerable areas in which the ancient crystalline rocks are exposed, whereas the northern platforms – the North American and Eurasian – have most of their areas covered by sedimentary rocks.

In addition, the ancient shields also differ in their types of mineralization: the South American shield, for example, is characterized by its extensive development of pegmatites, gold-ore deposits, and metamorphic deposits or iron and manganese. A feature of the South African crystalline shield is its rich tin-ore mineralization associated with acidic granites, as well as its deposits of platinum, chromium, nickel and diamonds associated with ultrabasic magma, which in turn is associated with the major faults in the later development of the continent. A peculiarity of the North American platform is its development of various hydrothermal deposits – gold and pyrite deposits of Archean and later ages, native copper deposits associated with Proterozoic basic extrusives, cobalt-silver deposits associated with the acidic differentiates of Proterozoic basic intrusives, nickel deposits associated with norites, etc. Another striking peculiarity of the North American platform is its development of telethermal lead-zinc ores in the limestones of its sedimentary mantle, which are more extensive here than anywhere else in the world. The Russian and Siberian platforms, finally, are characterized by the occurrence of basic, ultrabasic and hyperalkalic rocks along the margins of the crystalline shields, with their accompanying deposits (iron, nickel and rare elements).

Differences may also be noted in the nature of the metallogenic zones in geosynclinal regions. For example, the Variscian ore-bearing region of Western and Central Europe, which according to Stille (1949) is located at the inter-

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[4]Here and throughout the rest of this article, "basins of subsidence" and "uplift" will be understood to refer to the primary paleogeographic elements -- the intrageosynclines and intrageanticlines of geosynclinal systems -- and not to post-folding tectonic forms.--Ye. A. R.

section of two major geosynclinal systems, has a block structure in which the rhombic and rectilinear outlines of the crystalline massifs are bordered by zones of secondary subsidence. These zones of subsidence contain pyritic ores associated with the spilitic-keratophyric rocks belonging to the earlier stage of development. The crystalline blocks of the Erzegebirge contain tin, zinc, lead and other mineralizations associated with acidic granite intrusives of the later stages of Variscian folding.

The folding in these ancient crystalline blocks is of peculiar nature. Here one may note both folded structures in the basement, as well as the block-like dislocations characteristic of the later movements of this region. Lead and zinc deposits are also encountered in the faults which border the ancient crystalline blocks. It is incorrect to relate the tin-bearing granites of the Erzegebirge with the formations of the middle stage: the intrusions follow the fractures in the crystalline basement, and the granitic massifs here show all the features of post-orogenic formations; in the types of their rocks and the nature of their mineralization they correspond fully to the criteria of the middle stages, as defined in the metallogenic methods of VSEGEI. Thus, even at the beginning of this survey of ore provinces, we have already encountered difficulties in relating ore-bearing complexes to one stage or another.

A characteristic type of mineralization also appears farther south, in the younger tectonic zone of the Carpathians. The Alpine-Carpathian-Balkan zone cannot be compared to other zones in its tectonic structure. Having once been an area of subsidence between two large continental blocks, it is now characterized by the development of thrust structures[5] which are peculiar to it and are nowhere else manifested to such a degree. The existence of these horizontal thrust sheets is probably also the reason for the relatively weak manifestation of intrusive igneous activity in Alpine times and the slight development of post-magmatic deposits. Here the latter are characterized by very specific features. They are associated either with extrusives, which intersect the thrust sheets along faults, or else form metasomatic bodies far away from the igneous rocks – siderites, sometimes with sulfides (Maska, 1957), or else metasomatic sulfide deposits.

In Yu. A. Bilibin's scheme, these ore occurrences would be assigned to the late stages. But the artificality of this distinction appears in the fact that here we are dealing with combinations of stages, early and middle, as well as late.

Moving farther eastward, we come upon the unique metallogenic region of the Urals, characterized by a different structural position and different features of igneous activity and ore mineralization. The submeridional zone of the Urals lying between the Russian and Siberian platforms is characterized by the development of ultrabasic and basic intrusives associated with major faults in the earth's crust and accompanied by deposits of platinum, chromium, nickel, titanomagnetites, as well as by the development of a spilitic-keratophyric formation with its associated pyrite deposits. These igneous complexes, which according to the metallogenic methods of VSEGEI belong to the early stages, and are very clearly manifested in the Urals. In this case, however, throughout the greater part of the territory there are also evidences of middle and late stages, whereas the manifestations of the so-called early stages repeat themselves in time.

The metallogenic features of the Urals ore province will be taken up in detail below, since the Urals form a typical region of mineralization associated with basic and ultrabasic intrusives, as well as with volcanogenic rocks. The Urals ore province has a complex structure consisting of a series of parallel narrow ore zones extending along the folded structures and the faults that border them in the submeridional direction for thousands of kilometers. A considerable part of the ore-bearing structures of the Urals, especially in its eastern areas, in the Turgay basin, is covered by younger Mesozoic and Cenozoic deposits.

The mountain system of the Urals comprises a series of different structural-facies zones – ancient areas of uplift and subsidence. These structural depressions and uplifts are bordered by large faults, in which are located linear elongated intrusive masses of basic and ultrabasic composition, as well as acidic differentiates of the basic magma. In the Southern Urals, where the geosynclinal development continued longer within the Carboniferous Magnitogorsk basin, in the final stages of folding there was a development of granitic intrusives which terminated the last stage of igneous activity.

Different types of ore deposits are associated with the various types of structural-facies zones and faults; this is the reason for the zonality in the distribution of the metals. The fundamental structural unit of the Paleozoic Eastern Urals metallogenic region is the so-called Zelenokamennyy (Greenstone) synclinorium, which extends along the Urals for thousands of kilometers. In the area of the Urals, this zone of basic and moderately alkaline extrusives of Paleozoic age is divided by an uplift (Shtreys, 1951). The volcanic rocks are

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[5] The conception of the existence of enormous thrust sheets in the Carpathians, as in the Alps, as is well known, is a very controversial one.--Russian Editor.

thickest along the margins of the synclinorium, where there are faults which were repeatedly reopened and served as channels for the volcanic outflows. In these same marginal parts of the synclinorium there are chains of pyrite deposits – a western and an eastern chain.

The deposits are associated with the greenstone formation and do not extend beyond the limits of its area. In the area of the Ufa plateau, where the Urals form a steep arch-shaped bend, and the structural-facies zones become narrower, the pyrite zones approach each other and finally merge into one. Farther southward, as the folded zones of the Urals widens and straightens out again, where the folded zone plunges southward the Greenstone belt is again divided into two zones by the superimposed Magnitogorsk basin, already mentioned above as an area of Carboniferous deposits. In this section the two greenstone zones appear on the flanks of the Magnitogorsk synclinorium.

The pyrite deposits differ in attitude in different sections of the Greenstone zone. In the Middle Urals they are associated with large zones of cleavage and intensive metamorphism, and are localized in zones of quartz-sericite rock. The deposits associated with zones of folded extrusive rocks were formed before the end of the volcanic activity, since they are intersected by dikes and covered by the flows of the upper member of the Silurian volcanic complex, consisting of orthophyres and their tuffs (Loginov, 1955).

Hydrothermal metamorphism, the last manifestation of which was the formation of the pyrite deposits, occurred after the intensive cleavage of the volcanic rocks containing the ore[6]; this was evidently produced by solutions originating at great depth.

In the southern part of the Urals the deposits of pyritic ores occur in non-metamorphosed or slightly metamorphosed extrusive rocks which have not been subjected to such intensive deformation as the extrusives of the areas farther north. Here, too, the mineralization is localized in a "fork" of volcanic rocks; it occurs in the lower series of acidic extrusives but does not extend into the overlying series of porphyrites. The regular association between pyrite ores and areas in which the acidic extrusives are of considerable thickness has caused some investigators to believe that the mineralization is connected with volcanic structures and rocks. Even if this is the case, however, there can still be no doubt that here, too, the solutions originated at great depth, since the mineralization can be traced vertically down to 900 meters.

Thus, the pyritic deposits were apparently not formed at the same time, but under different conditions in different areas. In the Northern Urals, in the area of earlier uplift, the tectonic dislocations which led to the formation of the pre-ore zones of folding and metamorphism occurred earlier. In the Southern Urals, where the geosynclinal subsidence continued for a longer time, intensive pre-ore deformations did not occur and the formation of the ores was more closely associated with the volcanic activity itself, although here too it had its ultimate origin in deep-seated magma chambers.

This example of the pyritic deposits of the Greenstone zone of the Urals shows that the conditions of ore mineralization can differ in different sections of a single elongated zone. Moreover the specific features of the mineralization in different districts are determined by the peculiarities of development of the various parts of the ore-bearing zone. Here the determining features of the metallogeny were the transverse structures – areas of earlier uplift and prolonged subsidence, which led to the formation of different types of ore districts characterized by different tectonic regimes of development of the ore-controlling zones.

Along the margins of the Greenstone synclinorium lie chains of basic and ultrabasic rock masses. In the west is a chain of elongated masses of basic rocks and their differentiates, whereas in the east there are mainly masses of serpentinites formed from the ultrabasic rocks. The massifs of the western gabbro-peridotite zone are complex. The lower surface of the intrusive series, which is inclined toward the east, contains massifs of ultrabasic rocks. The axes of these massifs are composed of gabbros, the predominating rock in this igneous complex. Farther to the east there are discontinuous masses of acidic differentiates of the gabbroic magma – plagioclase granites and syenites. The latter, according to Ye. A. Kuznetsov, form the upper surface of the complex intrusive series. It is interesting that the gabbroidal rocks are partly of metasomatic formation, resulting from granitization and metamorphosis of the porphyrites in the Greenstone series, as pointed out by V. A. Artamonova in the case of the Barancha massif. It has also been established that there were other complex transformations leading to the development of ultrabasic rocks from the gabbros and, on the other hand, of gabbros from ultrabasic rocks. In other words, metamorphic processes played an important role in both the formation and alteration of the

[6] The manifestation of later post-mineralization dynamic and hydrothermal metamorphism occur everywhere (T. N. Shadlun), but are generally a detail against the background of the pre-mineralization metamorphism, which is immeasurably more intensive.-- Ye. A. R.

basic and ultrabasic rocks of the Urals, and these processes have recently attracted more attention on the part of geologists.

The ore-forming processes themselves occupy a particular position among these complicated metasomatic alterations. Specific types of deposits are associated with the various types of rocks occurring within different zones; this is the reason for the elongated linear ore belts and zones. For example, with the pyroxenite massifs occurring in the western part of the gabbro-pyroxenite zone are associated deposits of platinum, and with the gabbroidal massifs are associated deposits of titanomagnetites and disseminated copper ores. Finally, with the acidic derivatives of the gabbroids, the syenites, east of the zone of basic rocks, there are associated skarn deposits with magnetite and copper mineralization located on the contacts between these massifs and the rocks of the sedimentary tuff series that surround the interlayers of carbonate rocks (Blagodat' Mountain, Vysokaya Mountain, etc). Still farther east, along the other side of the Greenstone basin (along the fault which borders it on the east), there extends another zone of syenite massifs accompanied by a second zone of skarn rocks. Thus, like the pyrite deposits, the skarns form two symmetrical zones along the margins of the Greenstone basin. Farther out, toward the periphery of the basin, the general symmetry is broken by the predominant development not of gabbroids, but of the serpentinites of the so-called chromium zone of the Urals, which is known for its large deposits of chromite, asbestos and other minerals associated with hyperbasite intrusions.

Up to now we have been discussing the metallogeny of the "femic profile", associated with basic and ultrabasic magma and its derivatives. But the Urals also contain another type of mineralization, of the "sialic profile", containing deposits of gold, tungsten, and rare metals associated with the later massifs of granites and partly of alkaline rocks. The Carboniferous granitic intrusions occur mainly on the eastern slopes of the Southern Urals, where they form a chain of rather large bodies associated with the zone of sandstones and shales of the Magnitogorsk basin. With these relatively early granitoids and especially with intrusives and dikes, all of which have a higher content of basic elements, are closely associated gold-ore deposits which form an elongated gold-bearing zone observed as early as 1877 by I. V. Mushketov. With the later massifs of acidic granites are associated deposits of rare metals – tungsten and also precious gemstones. Finally, the alkaline massifs (syenites and miakites) also have their own associated rare-metal deposits. These alkaline massifs of the Il'men-Vishnevogorsk complex are localized in a narrow fault zone along the western margin of the Greenstone basin, which, like the zone of gabbroidal rocks, contains clear manifestation of metasomatisms in the formation of the ore-bearing rocks. The terminal stage in the intensive processes of alkaline metasomatism was the formation of mineral bodies with their peculiar niobium-zirconium mineralization.

One peculiarity of the Urals ore province is the fact that it occurs in a system of close parallel faults in the earth's crust, which descend to great depths and have been repeatedly reopened during the development of this folded zone. Since the formation of basic rocks and the differentiates of basic magma embraced a very long period of time in this area (from the Silurian to the Carboniferous inclusive) and took place in repeated stages, the term "early" stages of igneous activity is artificial and inappropriate for these complexes of rocks.

The particular metallogenic features of the Greenstone belt of the Urals and its analogs have been determined not by the time of formation of the igneous rocks, but by their development in zones of deep faults. The latter have repeatedly opened passages for magma and active solutions, which have caused intensive metamorphic alterations leading to the formation of gabbroids or alkaline rocks and pegmatites of metasomatic character, and have caused the already existing crystalline rocks to change their composition, along with the formation of extensive zones of various hydrothermal alterations, the latest members of which are the ore bodies of various types of deposits.

This brief description of the principal magmatic ore occurrences in the Eastern Urals shows the extraordinary variety of types of deposits to be found in its ore districts. The endogenic deposits of various kinds here are localized in very narrow linear zones and belts, which can be classified into the following types.

1) Zones of deposits of chromite, platinum, associated with ultrabasic rocks, copper-vanadium and titanomagnetite ores associated with basic intrusives that lie in deep faults repeatedly renewed during various geologic periods.

2) Zones of iron-ore and copper-ore skarns which are also clearly oriented along the same faults as narrow belts extending along the contacts with syenite and plagioclase granite massifs.

3) Zones of pyrite deposits associated with specific strata of extrusives, and in places with zones of folding and intensive pre-ore alterations in the volcanic series. These narrow "belts" may be traced for many scores of kilometers along their trend, but are comparatively small in width.

4) A zone of rare-metal mineralization associated with a belt of alkaline rocks of the Il'men-Vishnevogorsk complex.

5) Zones of gold-ore mineralization associated with narrow and elongated belts of dike rocks.

6) A zone of tungsten mineralization associated with acidic granites.

Within the Urals metallogenic province, however, along with these elongated zones one may also distinguish transverse metallogenic units – ore districts and areas associated with the transverse tectonic elements of this enormous folded zone.

The main transverse structure of the Urals, which determines the geologic structure and metallogeny of its northern and southern parts, lies on the continuation of the Ufa plateau. The folds of the Urals form an arc-like bend around this mass. According to N. S. Shatskiy (1945), the Ufa plateau, which bulges eastward into the Urals, is a very ancient uplift. The Paleozoic geosynclinal basin as it were moved around this ancient uplift. Later in this area appeared the transverse bend of the Urals folded system, which "sharply divides the Urals folded structure into its northern and southern parts, each of which has its own structure and history" (Shatskiy, 1948, p. 40).

Deep faults appear with special clarity in the area of this arc-like bend. Here one may see very large massifs of basic and ultrabasic rocks, Silurian extrusives of a peculiar nature, and massifs of plagioclase granites and syenites occur distinctly and in their complete development. This area, located north of Ufaleya, has been distinguished by L. N. Ovchinnikov (1957) as an area of particular development of skarns. Here are concentrated deposits of platinum, associated with a gabbro-peridotite formation. Here there are also pyrite deposits which are clearly of post-volcanic formation; these arose in zones of folding, cleavage and intensive alteration of the extrusives, after all these processes had taken place, but in association with the continuing volcanic activity of later phases.

As an independent ore district one may also distinguish the bend in the Urals structure, where the folds are most tightly compressed. Here, within a comparatively brief interval, in a zone of young faulting, there was an intense manifestation of alkaline metasomatism which may also have led to the formation of the Il'men-Vishnevogorsk alkaline complex and its associated deposits of rare elements.

The Southern Urals (south of Miass) also has its own peculiar tectonic and metallogenic features. Here the folded zone becomes wider, along with a general plunge of the structure. The dynamic stresses were here evidently less intensive. Moreover it is interesting that the history of this part of the Urals geosyncline differed somewhat from that of the rest. The extrusives, here represented by spilitic-keratophyric rocks forming two zones on the flanks of the synclinorium, did not undergo any deformation and metamorphism before the formation of the pyritic ores. The pyrite deposits themselves are much more closely associated than in the Northern Urals with extrusives formed during the period when the volcanogenic activity originated, but were apparently also produced by solutions emerging from the depths, from the same magma chambers which gave rise to the extrusive formations. The geosynclinal regime in the residual Magnitogorsk basin continued longer in the Southern than in the Northern Urals, and after its inversion there was a formation of younger granitoids with their associated iron-ore contact deposits and the tungsten and rare-metal deposits associated with their more acidic varieties. Gold-ore deposits are connected with minor intrusives associated with a system of elongated fractures. The Urals as a whole, and especially its Greenstone zone, may be distinguished as a type structural-metallogenic unit–a femic ore province with a predominance of basic magmas.

A completely different structure is found in the metallogenic region of the Caucasus. A continuation of the Tertiary Mediterranean belt, this region also has specific features peculiar to itself. In the first place, the Caucasus is a polycyclic, metallogenically complex region, divided into the narrow structural-metallogenic zones of the Ciscaucasus, the Front Range, the Main Caucasus Range, the Southern slopes and its Southern continuation in the zone of the Lesser Caucasus – the Dzirul', the Adzharo-triality, the Somkhet-Karabakh, the Kafan, the Sevan-Kurdistan and the Miskhan-Zangezur mountains (Tvalchrelidze, 1958). These structural-metallogenic zones have different histories and are characterized by deposits of different ages and types of mineralization. The structural-metallogenic zones contain ore zones, and the latter contain ore concentrations.

The metallogenic region of the Caucasus differs from the other young metallogenic zones of the Mediterranean belt. The Caucasus is characterized by large vertical faults bordering basins of various ages and serving as channels for the penetration of basic and ultrabasic magma. Certain zones of the Caucasus may be assigned to the femic profile. The igneous rocks and ore occurrences of the femic type in different zones have occurred at different times, but have nevertheless maintained their similar features without alteration. For example, pyritic deposits in zones of various ages, beginning with the Paleozoic (the Front Range) and ending with the Mesozoic and the Tertiary (the Transcaucasus) are associated with spilitic-keratophyric and keratophyric formations. Similarities in geologic position, associated igneous rocks and characteristics of deposits may also be seen in the chromite

and nickel mineralizations of various ages, and in the titanomagnetite ores, of which the former are associated with ultrabasites, and the latter with gabbroidal rocks (Caledonian deposits in the Main Caucasus Range, Variscian deposits in the Front Range, and Mesozoic and Tertiary deposits in the Sevan-Kurdistan zone). There is also a similar repetition in the metallogenic zones of various ages of similar types of ferrous and non-ferrous metal deposits associated with granitoids.

From these similar features of deposits of various ages and their associations with specific igneous formations G. A. Tvalchrelidze has distinguished, in all the metallogenic zones of various ages, sedimentary, magmatic and ore complexes of three stages – pre-folding, folding and post-folding, this modifying Yu. A. Bilibin's principle of metallogenic subdivision in regard to the complex polyciclical region of the Caucasus. It must be noted, however, that the existing generalizations regarding the metallogeny of the Caucasus, which divide the deposits according to their age, must still be supported by special investigations, since the ages of the deposits have still been determined only tentatively.

In addition, the zones of various ages also have their own peculiarities. For example, pegmatites with small amounts of rare-metal mineralization occur in association with the Caledonian granites of the Main and Front ranges of the Greater Caucasus. The Mesozoic rare-metal mineralization and also the Tertiary mercury and arsenic deposits are associated with fault zones in these same ancient structures. The Mesozoic polymetallic deposits are localized both in ancient structures and in the younger basins surrounding them, as well as along zones of faulted dislocations. A characteristic feature of the ore zones of the Greater Caucasus is thus the polycyclical nature of the mineralization. A peculiarity of the metallogenic zones of the Lesser Caucasus is the appearance of volcanogenic rocks of Mesozoic and Tertiary ages and of intrusions close to the surface, accompanied by various types of deposits of which the Tertiary copper-molybdenum deposits are the most prominent.

In general, the Caucasus provides an interesting example of a polycyclical ore province with mineralizations of various ages, partly associated with particular zones and partly superimposed upon zones of ancient metallogeny through regional and local faulting. Moreover the Caucasus is also of interest as an example of an ore region which contains both femic and sialic types of mineralization. The occurrence of metallogenic zones of both types is probably due not only to the time of formation of the igneous rocks and the ores, but also to the geologic structure of these zones. The production of zones of the sialic type requires rocks of aluminosilicate composition, including the deepest parts of the section, whereas zones of femic type require the presence of fractures penetrating to the deep-seated basic magma chambers.

The example of the Caucasus shows the need for precise differentiation in the approach to metallogenic analysis of areas of polycyclical mineralization, taking account of the age, as well as the structural position, of the metallogenic zones and districts.

The nature of the metallogeny and the dispositions of the ore districts and ore concentrations in the Caucasus have been determined not only by longitudinal but also by transverse tectonic elements trending in the so-called anti-Caucasus direction. The latter are apparently a reflection of the long-lasting dislocations of the Cisurals area, which were manifested on the platform as zones of meridional and northeastward uplifts (the Pugachev, Vyatka, etc. zones) and zones of large basins (the Ul'yanov-Saratov zone). Similar broad and gentle deformations on the platform map perhaps reflect the deep structures of the crystalline basement (Shatskiy, 1948). The latter are oriented parallel to the Proterozoic geosynclinal zone of the Urals. Thus, the Caucasus ore province is also characterized by the occurrence of transverse tectonic elements which have affected the metallogeny of the ore districts. The importance of these transverse uplifts in the structures of the Caucasus has been pointed out by V. P. Rengarten (1929).

The ore region of Central Asia is another example of a linear metallogenic zone, connected with the folded system of the Tien Shan mountains. Here the chronological differentiation of the metallogenic areas appears on a large scale. One may readily distinguish, for example between the northern region of Caledonian folding on the margins of the Angara continent, and the southern region of Variscian folding. Variscian metallogeny also appears in the northern part, along faults in the ancient folded complex and especially at the junction between the Caledonian and Variscian metallogenic regions along the chief structural line of the Tien Shan (Nikolayev, 1933), with which various polymetallic and rare-metal deposits are associated.

In the Southern Tien Shan, as Ye. D. Karpova (1959) has observed, one may see the clear association between deposits of various types and the various structural-facies zones. For example, in this region she has distinguished two geosynclinal (the Fergana-Kokshaal' and the Chatkal-Naryn) and two geanticlinal (the Kuramin and Gissar) zones, characterized by different histories of development and differences in metallogeny.

The principal (orthogeosynclinal) basin – the Fergana-Kokshaal' zone – is characterized by prolonged subsidence and accumulation of thick terrigenous deposits, as well as carbonate deposits in the upper part of the section. The specific features of this zone are the development of tungsten and in places of tin deposits, which are of the quartz type where the mineralization occurs in aluminosilicate rocks, and of the skarn type among limestones. The latter is the principal type. Along the margins of the Fergana'-Kokshaal' basin extend zones of antimony-mercury mineralization coinciding in space with the zones of ophiolites. Although the basic and ultrabasic rocks of the ophiolite zone are not developed on a great scale, they are of some interest in regard to their metallogeny. They correspond not only to the early pre-folding stage, but also, according to Ye. D. Karpova (1959), were partly formed in the later stages as well – in the period of the main folding. Thus, here, as in the Urals and the Caucasus, the ophiolites are characteristic not so much of particular stages of igneous activity, but rather of specific structural zones – with elongated and deep faults which have repeatedly penetrated into the deeper parts of the earth's crust. It is typical that the later antimony-mercury ore occurrences also gravitate toward these zones of structural weakness.

Other metallogenic features are to be seen in the geanticlinal (Kuramin and Southern Gissar) areas and the peripheral geosynclinal basin of the Chatkal-Naryn zone; here lead and zinc deposits predominate (Karpova, 1959).

An interesting detail of the metallogeny of Central Asia is the rare-metal mineralization associated with alkaline rocks and the intensive alkaline metasomatism along the faults of the principal structural lines in the Tien Shan region. This association between alkaline metasomatism and alkaline rocks and their accompanying rare-earth and rare-metal deposits and fault zones has already been pointed out above in the case of the Urals (the Il'men-Vishnevogorsk zone).

Similar phenomena will be pointed out in the case of the other ore regions, where they distinguish zones of large structural seams as major structural-metallogenic elements.

North of the Central Asian ore region lies the complex metallogenic province of Central Kazakhstan, in which, as in Central Asia, there is a sharp predominance of granitic magma with its accompanying complex of rare and non-ferrous metals. This ore region differs morphologically from the linear zones of the Urals, the Caucasus and Central Asia. Here the territory has a block structure: the block-like massifs are, so to speak, connected by a system of folded zones that surround them. This tectonic structure has apparently been determined by the intersection of major tectonic zones trending in different directions: the subequatorial belt of Central Asia and a submeridional zone covered by younger sediments, which is the continuation of the Urals structure. This complex region, located at the intersection of major tectonic elements of the earth's crust, contains various types of ore districts and mineralizations of various ages.

The ancient crystalline blocks contain occurrences of Precambrian mineralization (tin, gold, iron) as well as superimposed younger (Paleozoic) deposits associated with faults. The surrounding zones of Caledonian and Variscian folding, which are in turn differentiated into internal zones and subzones, contain deposits of pyritic, lead-zinc, rare-metal and other ores. It is no coincidence that in this trough-and-block structure of the Central Kazakhstan ore region one sees not elongated linear zones, extending for hundreds of thousands of kilometers, but frequently isometric ore concentrations associated with the points of intersection of regional tectonic faults running in different directions. The importance of the disruptive dislocations which sometimes intersect different structural-facies units here may be seen very clearly. As in the Caucasus, in this polyciclical ore region one must first of all distinguish the zones of various ages, the igneous and ore formations. This has been the basis for the metallogenic maps constructed under the direction of A. I. Satpayev by the Geological Institute of the Kazakh Academy of Sciences (Satpayev, 1953, 1955).

In Central Kazakhstan K. I. Satpayev distinguishes a large number of ore formations characteristic of different tectonic-igneous cycles. Some of these formations are repeated in time, and others occur only at particular stages. Different conditions lead to the concentrations of different metals: for example, lead and zinc occur at the contacts of intermediate granitoids with limestones (in the Aksoran-Akdzhal' zone) and volcanogenic rocks, the rare-metals and tin are associated with the alaskites that occur in an aluminosilicate medium, gold is associated with granitoids that have a high content of basic elements, and nickel, chromium and asbestos are found among hyperbasites. Since the various types of igneous rocks are localized in different zones of secondary and tertiary order, the deposits have a zonal distribution in this region as well, although the zones are not as clearly delineated as in the linear folded zones of the Urals, the Caucasus and Central Asia, and the zones themselves do not extend for such great distances.

The metallogenic zones have a more clearly linear form in the Altay-Sayan Mountain region, which projects into Mongolia and into the Transbaykal. A peculiarity of the Altay ore region is its differentiation into zones of parallel up-

lift and subsidence, producing the parallel ore belts of the Gornyy Altay, the Rudnyy Altay and Kalba. Moreover the chief Paleozoic basin (the Zaysan geosyncline), composed of sandstone and shale strata, is characterized by the development of tin and rare-metal mineralization, whereas the zone of relative uplift and faulting where extrusive rocks have developed, contains the copper-polymetallic zone of the Rudnyy Altay (Gorzhevskiy, Kozerenko, 1956).

The zone of deep faults of Western Siberia contains a metallogeny of the femic profile, associated with Caledonian basic and ultrabasic intrusives accompanied by deposits of chromium, nickel, talc and asbestos. Skarn iron-ore deposits are associated with the differentiates of this basic magma, the granitoids with a high content of basic elements. Finally, the zone of faults, whose distribution parallels that of the ophiolite zone, contains mercury ore deposits – that is, there is a repetition of the structural association between the ophiolites and the later mercury occurrences along the same zones of deep faults at the borders between the different primary structural-facies zones.

Certain peculiar regularities may also be seen in the distribution of the ancient gold deposits of the Sayan, which form a zone in the ancient metamorphic rocks and the granites that intersect them (Obruchev, 1911). Along with the Caledonian granites, the Sayan area contains acidic pegmatites, whereas rare-metal deposits are associated with alkaline rocks along regional faults. Thus, this area also shows a zonal ore distribution, the ore zones localized in definite structural-facies zones and also connected with major faults of regional character.

Still farther to the east lies the ore province of the Transbaykal, with its polyciclical development. Since the Proterozoic this region has been a geosyncline of inherited development, with folding occurring during Caledonian and Variscian times, accompanied by the injection of large granite massifs. Beginning with the Permian, this region has been the site of a younger basin, a deep embayment of the Pacific Ocean geosyncline, the marine conditions being preserved in the residual basin into the Middle Jurassic, after which the geosyncline came to an end with a local inversion and with the injection of younger Jurassic-Lower Cretaceous intrusives. As in Central Asia and in the main area of subsidence of the Altay, there was an accumulation of thick terrigenous deposits, with a tin-tungsten mineralization occurring after the end of the geosyncline and the intrusion of the acidic granites. The zone of uplift, composed of limestones, has produced a polymetallic zone. A zone of gold-molybdenum deposits, finally, extends along the margin of the folded region.

The zonal distribution of the ore deposits in the Transbaykal has been observed long ago (Doktorovich-Grebnitskiy, 1916, Smirnov, 1936). S. S. Smirnov's scheme (1936) which distinguished the three zones mentioned above – a northern zone of gold-molybdenum mineralization, a central zone of tin-tungsten mineralization and a southern zone of polymetallic mineralization – has been somewhat disrupted as a result of recent discoveries, such as that of a southern molybdenum zone and a series of secondary metallogenic zones. Nevertheless the general zonal distribution of the metals, with specific deposits concentrated in the zones described above, still remains in force.

This regular association of tin with terrigenous deposits, of lead and zinc with zones of carbonate rocks and of gold with regional faults, as will be shown later, also appears in other ore regions of similar type.

Within the elongated linear zones there are areas with different mineralization. For example, the tin-tungsten zone of the Transbaykal over much of its extent is characterized by the development of numerous deposits of the quartz formation; in individual blocks, which are usually elevated like horsts and more eroded, there are pegmatites (in the Western Chikoy and the Borshchevochnyy areas); finally, in the fault zones that surround the Aga interior massif and are marked by pre-ore volcanic rocks, there are deposits of the cassiterite-sulfide formation. The latter are relatively few in number, but are of particular interest. Cassiterite-sulfide deposits are also encountered among limestones in the polymetallic zone. These deposits, which also include tin and lead-zinc ores, are the intermediate link between the tin and polymetallic mineralization that are distinguished as separate types in this article.

Still farther to the east lies the area of the Greater and Lesser Khingan and the Burea Range. This region also has a block-and-trough structure at the intersection of tectonic elements trending in different directions: the equatorial Mongol-Okhotsk zone of Central Asia and the submeridional Eastern Asiatic or Pacific Ocean belt which originates in China. Its clearest features are block dislocations in the fractured ancient platform, which contains superimposed basins surrounded by rigid exposed areas of the broken crystalline basement. Here the structural forms are very large, some of the basins being comparable to geosynclinal zones in size.

In the southern part of the Soviet Far East there are various types of structures: ancient blocks composed of Archean and Proterozoic crystalline rocks of the basement, Sinian-Cambrian geosynclinal zones characterized by sedimentary-metamorphic iron-ore formations, and zones of Paleozoic and Mesozoic basins, which have been transformed in folding into anticlinoria

whose cores contain large granitoid massifs. These structures typically contain tin, tungsten and molybdenum ores.

Finally, the late stages in the development of this region saw the appearance of large regional faults paralleled by zones of Late Cretaceous extrusives in superimposed basins, containing tin-ore deposits associated with subvolcanic facies or with the deep sources of this volcanic complex. In the same late stage, or even later, were formed the deposits of gold, antimony and mercury that are concentrated along the faults at the margins of the rigid massifs.

A different metallogeny is to be seen in the Northeastern USSR, which is characterized by extensive zones of Mesozoic folding surrounding the Kolyma massif. In this region large areas are filled with interconnected broad zones of folding, forming a great loop around the Kolyma massif, with branches running off to the northwest around the northern margin of the Siberian platform and to the northeast toward the Bay of Chaun and the Chukotka peninsula. A similar branching occurs in the southeastern part of the Kolyma-Yana-Chukotka zone, forming a broad funnel turned toward the Pacific Ocean, with its southern branch turning southward toward Dzhugdzhur and its northern branch turning northeastward.

This enormous system of folded zones extends for many thousands of kilometers and is also very broad. It arose in an area of subsidence on the platform, and thus contains neither rectilinear structures nor zones of ultrabasic rocks, which are typical of the metallogenic regions of the Urals type associated with major faults in the earth's crust. In the Late Paleozoic and the Mesozoic this was an area of rapid accumulation of thick layers of sediments forming a uniform flysch series of sandstones and shales. During the period of Mesozoic folding, a series of folds was formed surrounding the platform structure (Pushcharovskiy, 1955) and thereafter, mainly in the postfolding period, were formed chains of intrusive masses which are associated predominantly with faulted rather than with folded structures.

The variety of the metallogeny in this region is due to rocks of the granitoidal series. The earliest to be formed were the gold-ore veins connected with narrow, locally limited zones of minor intrusives trending mainly along the southern part of the Yana-Kolyma arch. The large granitoid massifs along the periphery of the Kolyma massif, located in a system of faults, contain zones of rare-metal mineralization "with deposits of tin, tungsten, molybdenum, arsenic and cobalt grouped around satellites of the Late Jurassic Kolyma granitic batholiths" (Matveyenko and Shatalov, 1958). Zones of this type include the Northern and the Main zone surrounding the Kolyma massif, and the Taskystabyt zone around the Okhotsk massif and the El'gin area of gentle dislocations (Matveyenko and Shatalov, 1958). These zones contain various deposits, principally of the quartz formation.

In the zone of the Main basin, on the other hand, which is filled with the sandstones and shales of the Verkhoyansk complex and surrounds the Kolyma massif in its center, there are cassiterite-silicate and cassiterite-sulfide deposits associated with fault zones that diagonally intersect the folds. These deposits are often physically associated with small intrusive bodies of granitoids with high content of basic elements; these may perhaps be hybrid facies of the granites (Padalka, 1939).

It is interesting that on the continuation of these same ore-controlling zones, where they extend into the neighboring zones of the Verkhoyansk anticlinorium and where older rocks are exposed, polymetallic deposits, sometimes also with tin, are developed (Imtandzha and elsewhere). Thus here, too, the mineralization is affected by the composition of the rocks that compose the given zone, and one may see an association between the tin and the zone of terrigenous rocks in an area of prolonged subsidence, and of lead and zinc with zones of anticlinoria, where the rocks of the lower structural stage which are principally of carbonate composition are close to the surface or are exposed.

On the east, the zone of Mesozoic folds is bordered by the broad Priokhotsk belt of Cretaceous extrusives, which lies almost at right angles to the branches of the Mesozoic folded zone, stretching between the latter and the Tertiary Karyak-Kamchatka geosyncline. This belt follows a system of deep faults along the boundary between two structural regions of different ages, and forms one of the links in an extensive discontinuous ring of volcanites along the periphery of the Pacific Ocean basin.

Another peculiarity of the eastern Priokhotsk zone is the occurrence of molybdenum mineralization associated with Cretaceous granitoids (granodiorites). This zone also contains tin mineralization of the cassiterite-sulfide formation associated with the Paleogene magmatic cycle (in the Omsukchan ore district). The distribution of the deposits in this district, as in the main Verkhoyansk basin, is governed mainly by faults oriented at an angle to the folding (here at right angles).

The extensive region of the Soviet Northeast is an example of a province of the sialic type with a clear predominance of granite, the most typical being the acidic granites of the alaskite series, although in places this province also contains occurrences of basites and ultrabasites with complexes of mineral deposits associated

with them (chromium, nickel, etc.). Deposits of this type include the zone of the Dzhugdzhur range, where such igneous rocks are widespread. The Dzhugdzhur zone is apparently characterized by the development of deep faults occurring at the bend of a system of folds surrounding a projection of the Aldan massif.

Ore districts of the femic profile are also characteristic of the younger Koryak-Kamchatka folded zone farther east. Here, too, the zones of basic rocks coincide with belts of mercury mineralization that are far from the sources of the magma, but are associated with the same zone of faults as the basic rocks themselves.

The Sikhote-Alin' region, part of the Pacific Ocean submeridional region, shows some features in common with the Yana-Kolyma area. This zone is associated with a Late Paleozoic and Mesozoic basin which, even in its early stages of development, was divided into interior zones of uplift and subsidence. Thus, as early as the Triassic there appeared a central uplift which later, during the process of folding, became the core of the Sikhote-Alin' anticlinorium.

From the standpoint of ore mineralization, the most important are the zones east of this uplift: the Eastern Sikhote-Alin' basin and the Coast Range uplift. These structural facies zones have had different developments. The zone of the main Eastern Sikhote-Alin' basin was characterized by prolonged subsidence and an accumulation of thick terrigenous deposits; the zone of the Coast Range uplift contains a much thinner mantle of sediments, among which there are limestones. Later along this zone appeared the great Coastal fault zone formed from a series of faults along the shore of the Japan Sea and reflected by a thick series of Late Cretaceous and Tertiary volcanic rocks of acidic and partly of intermediate composition. Nevertheless along the Central structural seam, following the boundary between the Central anticlinorium and the Eastern Sikhote-Alin' synclinorium, there may have been a process, more or less parallel to the volcanic activity that took place east of the Coastal fault zone, involving the formation of intrusives of granites and alkaline rocks of Late Cretaceous age.

These structural-facies zones, which are characterized by different complexes of sediments and different tectonic régimes during the formation of their igneous rocks and ore deposits, gave rise to ore zones with different metals.

In the Eastern Sikhote-Alin' basin, as in the Yana-Kolyma basin, there has been an extensive development of thick series of terrigenous deposits, and later on along this zone was formed the Sikhote-Alin' tin-ore zone. In contrast, a polymetallic ore zone occurs in the Coast Range uplift zone, where the section contains limestones as well as terrigenous rocks. Finally, along the fault that separates the Sikhote-Alin' basin from the Sikhote-Alin' central uplift, lies a zone of rare-metal and gold-ore mineralization (a subzone of the Central structural seam). Thus here, too, there is a regular localization of ore zones similar to that observed in other ore-bearing areas of the geosynclinal type: tin-ore zones occur predominantly in zones of sandstone and shale sediments in areas of prolonged subsidence. Polymetallic deposits, on the other hand, appear where the section includes limestones.

The nature of the mineralization is also affected by transverse tectonic elements. For example, with a transverse uplift in the folds of the Coast Range are associated rather large granitoid massifs accompanied by contact reaction-bimetasomatic skarns; at the plunge of this uplift are hydrothermal deposits far from the active source of the ore-forming solutions – hedenbergite-sulfide pipes which extend to the strata nearer the surface – and still farther along the plunge of the structure are cassiterite-sulfide vein deposits of the Bolivian type occurring among young extrusives and characterized by an abundance of sulfostannites and other sulfosalts (in the Sinancha district).

As in the ore districts of the Northeastern USSR, an important role in the distribution of the deposits has been played by fracture zones and by secondary igneous processes of various kinds.

West of the Mesozoic folded region of Sikhote-Alin' lies the Khankay massif, composed of Archean, Proterozoic, Sinian and Lower Cambrian series representing a fragment of the northern projection of the Chinese-Korean platform. This massif is one of a type of structures which Chinese geologists have called "rejuvenated platforms", characterized by comparatively gentle forms of dislocations and by faults with which various intrusives of different ages and in some places extrusives are associated. A characteristic feature of areas of this type is their polyciclical mineralization as well as certain other regularities of its distribution.

A concentration of tin in such regions is associated not only with aluminosilicates but also with carbonate rocks, where rich cassiterite-sulfide deposits occur. Here the carbonate deposits are represented partly by epicontinental marine sediments located in gentle basins such as syneclises. They are crumpled into gentle folds and form only the upper stage of the sedimentary mantle. Probably at depth intrusives were formed in aluminosilicate series here as well, thus facilitating the formation of specific tin-bearing leucocratic granites. The assimilation of the limestones at depth apparently did not disturb these processes of differentiation. Tin-rich granite has been injected into the gently dislocated carbonate series. The car-

bonate rocks have been very favorable for the deposition of ores, although cassiterite-sulfide deposits have not developed in the limestones, as usually happens whereas tungsten-quartz and cassiterite-quartz deposits have been formed in the granites and the aluminosilicate sedimentary rocks.

A special structural type of ore district in young metallogenic regions of the Pacific Ocean ore zone is formed by zones of faulting of the Coastal (Primor'ye) type, characterized by thick series of young extrusives. Ore districts of this type are characteristic of both the Asiatic and the American branches of the Pacific Ocean zone. They are associated with system of faults along the margins of the Pacific Ocean basin, extending for a considerable distance around it. The zones in which the thick series of volcanic rocks associated with the fault systems are developed are subaerial basins characterized by Late (Tertiary) folded deformations, although in particular and very gentle forms. Hypabyssal intrusives and deep magma chambers, and in places extrusives, are the locations of the various tin, lead and zinc, and sometimes mercury-ore mineralizations.

On the other side of the Pacific Ocean basin lies the enormous zone of the North and South American Cordilleras, famous for their rich deposits of gold and silver, and in places of tin and other metals. A characteristic feature of these regions is also the clear association between the ore deposits and major faults and their connection not only with intrusives but also in places with extrusives and subvolcanic formations. Within these four zones one may observe longitudinal zones of secondary and tertiary orders associated with structural-facies zones having various different histories.

In concluding this far from complete survey of ore provinces, we may note that the ore-bearing areas are extremely varied in their geologic structure and in the nature of their metallogeny, so that it is hard to find two ore districts that will resemble each other in detail. Nevertheless ore districts also have a number of similar features, so that one may attempt to classify them by type. Like any classification, such a grouping of ore territories will naturally be somewhat artificial and based on a schematization of all the various different factors. Nevertheless with such a systematization one can more easily understand the general laws governing the various phenomena and find a rational approach to the metallogenic study of ore districts of various types.

TYPES OF ORE PROVINCES, METALLOGENIC ZONES AND ORE DISTRICTS

In metallogenic provinces of various ages, and also in regions of different geologic structure (platforms or geosynclines), one may distinguish two geochemical types of ore districts – femic, characterized by the occurrence of basic and ultrabasic rocks, and sialic, characterized by a predominance of granitoids. The development of igneous rocks of one type or another is associated not only with the time or stage of evolution of the ore-bearing region, as would follow from Yu. A. Bilibin's conception, but also with the structural position of the given territory. For example, there are areas of specifically femic type (the Greenstone belt of the Urals), where basic and ultrabasic rocks determine the metallogenic profile of the territory. There are also extensive areas where basic and ultrabasic rocks are very much subordinate, and granites predominate. The ore regions and districts of these two types usually differ in structural position and in type of development. Femic regions are associated with major faults that penetrate into the depths of the earth's crust, whereas sialic regions occur under other structural conditions, in areas of plastic subsidence, and deep faults penetrating into the deeper strata of the crust are not characteristic of them. Geosynclinal regions of this type contain very few extrusives of the spilitic-keratophyric formation, and there is a predominance of terrigenous series, which affects the igneous activity and the ore mineralization associated with it.

The principal groups of ore-bearing areas on platforms and in geosynclinal regions, as well as in areas of the intermediate type – rejuvenated platforms and areas of block-and-trough structure – will be described below.

ORE DISTRICTS OF PLATFORMS

The crystalline shields of platforms are characterized by particular metallogenic features and by ore districts of their own peculiar types. These regions, especially in regard to endogenic mineralization, have been studied much less thoroughly than the ore districts of folded zones. This is due mainly to the fact that considerable parts of these ancient formations are buried beneath thick mantles of later deposits. Wherever the crystalline basement crops out at the surface it is highly eroded, so that if it contained ore deposits in the past, a great part of these has been removed. Nevertheless such platforms are still very rich in economic mineral deposits. They include many of the deposits of tin and rare elements: nickel, chromium and platinum (Africa), gold (Australia, Africa, North America and Siberia), iron ores and other minerals. All the details of geologic processes occurring in the Precambrian have yet to be studied, but there is no doubt that in many of their features they differ essentially from the processes of post-Cambrian times.

If one remembers that the Precambrian de-

velopment of the earth occurred over a length of time some five or six times greater than that of its post-Cambrian development, the quantitative importance of the phenomena which occurred in the ancient past becomes quite clear.

Platforms, in their present form, are the result of many various repeated processes, which have apparently changed their nature in time. There is no knowledge of the geologic phenomena that occurred during the first stages of development of the earth's crust. It may be that in these areas there was a concentration of ore elements, but that as a result of repeated remelting and granitization these ancient deposits must for the most part have been destroyed.

The presence of orthogneisses of various ages in other regions as well testifies that the formation of granites occurred repeatedly in the early stages of formation of the earth's crust. Apparently the most important during these periods were not igneous phenomena themselves, but processes of remelting and metasomatic alteration of the rocks, under conditions of high plasticity and frequently at great depths. The graphite deposits and pegmatites of ancient crystalline shields are associated with such processes of deep metamorphism. In general, these very ancient complexes are of little interest from the standpoint of ore mineralization.

Ore regions of another type on platforms are associated with zones of ancient basins and with the folded regions that arise on their sites. The processes of sedimentation, tectonic deformation and igneous activity in districts of this subgroup have their own specific features and differ in many respects from the processes of later districts.

A specific property of ancient deposits up to Late Proterozoic, and in places to Early Cambrian, in age (Khingan), is the extensive development of great iron-ore sedimentary metamorphic deposits such as ferruginous quartzites. The enormous area of the ferruginous beds exclusively within ancient rocks indicates that this corresponds to some peculiar conditions of their accumulation. The reason for this extensive accumulation of iron, which is not repeated later, may be the chemistry of the water (perhaps the oxidation potential in the hydrosphere and atmosphere of that time). The possibility is not excluded that the concentration of iron in the later period was also facilitated by the activity of certain organisms, which later on become extinct or were not preserved in highly metamorphosed rocks. In any case, the problem of the genesis of the sedimentary ferruginous quartzites has been and remains one of the enigmas in the study of ore deposits.

Not only the processes of sedimentation, but also those of deformation in sedimentary strata also took particular forms in these ancient periods. For example, the tectonic structures of ancient crystalline complexes are frequently gentle and smooth (Nikolayev, 1955), in comparison to the intensively folded forms of later folded zones; the other processes also change their nature with time. Igneous processes begin to play an ever greater role with the course of geologic time and, as in younger geosynclinal zones, within areas of ancient igneous activity one also notes a successive change from basic intrusives to acidic and hyperacidic, sometimes accompanied by pegmatites. As in younger zones, the ultrabasic rocks of ancient crystalline shield areas are accompanied by magmatic deposits of chromium, platinum and nickel, whereas the granites and pegmatites, since they contain rare elements, are characterized by tin and cassiterite-quartz deposits (Africa).

Enormous massifs of granites and the pegmatites associated with them are an essential feature of the African, Australian and other platforms. The deposits connected with these igneous rocks do not actually differ in nature from the later deposits formed in post-Proterozoic times. Gold deposits (in Australia) are extensively developed in connection with ancient granitoids.

A third subgroup is composed of regions of later deposits associated with faults in the ancient consolidated shields and with the strata of the platform sedimentary mantle that covers them; these occur in areas which we shall call epiplatform. The large fault zones, which are echos of the folding in the neighboring geosynclinal systems, are characterized by basic intrusives and their various differentiates – ultrabasic, alkaline and acidic – as well as basic and alkaline extrusives, with which specific mineral deposits are associated. For example, deposits of native copper and zeolites are closely connected with basic extrusives, whereas basic intrusives and their acidic differentiates (biorites) are sometimes accompanied by cobalt-nickel-silver ores and sometimes also by tin (Bushveld). On the other hand, basic and ultrabasic intrusives are the locations for copper-nickel mineralization and, in some places, for platinum and chromium.

A characteristic property of the later magmatic occurrences is their association with faults in crystalline shields running sometimes for hundreds of kilometers. Some of these faults extend through entire continents; a striking example is the submeridional zone of ultrabasic rocks in Africa, which according to Wagner runs for 500 kilometers.

On the other hand, faults in the crystalline basement sometimes arise at the margins of crystalline shields, in connection with the folding in the adjoining geosynclinal zones. Fractures of this type include the series of faults in the Kola peninsula, running parallel to

the Timan-Kana folded zone in a west-northwestward direction. Here the occurrence of ultrabasic rocks embraces the entire time from Precambrian to Devonian, and the faults were apparently repeatedly renewed.

The earlier of such formations include the Monchetundra and Pechenga ultrabasic massifs, which contain copper-nickel mineralization. Later formations are the complex differentiated Khibinsk and Lovozero massifs, with their unique combinations of rare-earth and rare-metal mineralization. These massifs were formed beneath a thin cover of extrusive facies and are thus also near-surface formations. Their most characteristic feature is the very complete differentiation, with physical separation of the various types of rocks into composite, frequently ring-shaped intrusives of the central type. This differentiation has also resulted in the formation of monomineralic rocks, which are themselves ores, such as the lujavrites that are a source of zirconium. Another special type of differentiate of these complexes comprises the carbonatites, which contain rare and rare-earth elements.

In these plutons of the central type with their zonal structure one observes a regular alternation, with olivine-containing rocks in the center and alkaline or ultraalkaline varieties along the periphery of the massifs. The peculiarities of these hyperalkaline products of basic magma are so great that there can be no doubt of the need for distinguishing the areas in which they are developed as a special type of ore district.

The ultrabasic and alkaline plutons formed among ancient rocks, in spite of their association with clearly faulted dislocations, in their detailed characteristics are also governed by the folded structures of these rocks. Sometimes one encounters layer-like intrusives that are bent into arch-like shapes on the map and appear to surround the cores of ancient folds (in the Monchegorsk zone). It may be that the inheritance of ring-shaped plicative structures of these domical folds has played some role in the development of the ring plutons of the central type.

Another type of mineralization is associated with traprock formations. Traps, the majority of which have been formed from non-differentiated magma of basaltic composition, occur at the surface of the sedimentary mantle overlying the ancient platforms (such as the Siberian and Hindustan). Iron-ore and copper-nickel deposits are associated with minor hypabyssal and near-surface intrusives of the same complex.

The intrusive analogs of the traprock flows occur for the most part at the periphery of tectonic blocks. On the Siberian platform, in particular, they appear to surround the Tunguska syneclise on the west, southeast and northwest, forming a relatively rectilinear zone (Krasnov and Masaytis, 1955).

Here as well the different ore occurrences are associated with the various types of minor intrusives, so that one may distinguish areas of different mineralization. For example, with the non-differentiated massifs of basic composition and partly, perhaps, with their acidic diorite differentiates, are associated the peculiar and variegated magnetite deposits of the Angara-Ilim region. On the other hand, the copper-nickel mineralization of Noril'sk is connected with certain varieties of basic intrusives. The ore-bearing intrusives in this region, concentrated along a major tectonic zone of submeridional trend, are directly controlled by faults of smaller orders, running in the north-northeastward direction. As in the case of the older ultrabasic intrusives in the northern part of the Baltic shield, the mineralization here is very closely associated with gently sloping intrusive bodies and does not occur outside them. There are various views of the relationship between the nickel-bearing intrusives of Noril'sk and the basic massifs of the traprock formation. According to Yu. M. Sheynman (1955), they were formed more or less at the same time, but under different conditions.

Another type of ore district includes the areas in which diamonds occur. On the Siberian platform the diamond-bearing kimberlite pipes are localized in a zone of deep faults along the northeastern margin of the Tungusska syneclise; in this regard they resemble the famous diamond-bearing kimberlite pipes of the African deposits, which are also connected with systems of major faults.

Finally, a completely independent group of ore districts on ancient platforms includes areas of telethermal lead-zinc and fluorite mineralization that are far removed from igneous rocks. These deposits are localized in the carbonate rocks of the platform sedimentary mantle, occurring primarily in definite strata which are most favorable to their emplacement. Analysis of the tectonic structures of the lead-zinc ore districts of this type (Mississippi and Missouri) shows that the localization of these deposits is affected by very peculiar dislocations.

An important role in particular has been played by consedimentational arches forming gentle upwarps and domical forms containing exfoliation fractures; these serve as the paths for the ore-bearing solutions (Turner, 1958).

The genesis of these deposits remains controversial, as before, although the majority of investigators are definitely inclined to the view that their formation is postmagmatic and is associated with deepseated intrusive rocks.

The signs of igneous activity in these areas, which are far removed from folded zones and zones of intensive igneous activity, are the frequently encountered alkaline and basic dikes. The formation of the telethermal deposits on platforms may also be an echo of the more intensive igneous and ore-forming processes occurring in the adjacent folded zones.

ORE DISTRICTS OF GEOSYNCLINAL REGIONS

The ore provinces of geosynclinal regions may, according to their geochemical properties, be subdivided into femic and sialic categories.

Ore Districts of the Femic Type in Linear Geosynclinal Zones

Ore regions and districts of the femic type occur along major linear faults. These are eugeosynclinal regions, characterized by the occurrence of intensive volcanic activity in the early stages and by the development of volcanogenic rocks of the spilitic-keratophyric formation. Extrusives of volcanic craters and later intrusive massifs of basic and ultrabasic composition are associated with faults and occur as narrow, linear zones.

It is interesting that certain types of basic and ultrabasic rocks, as well as later alkaline rocks, as would appear from the example of the Urals, have to a considerable degree developed metasomatically. Intensive metasomatism also has occurred in the hydrothermal stage, leading to the formation of large zones of quartz-sericite rocks and pyritic deposits.

The ore occurrences in zones of the femic type have similar features in ore provinces of different regions of the earth, but the processes of their formation may have been different. As an example, we may cite the pyritic deposits physically associated with volcanic rocks of the initial stages. These deposits, with all their outward similarity and their constant association with extrusives of the spilitic-keratophyric formation, may have been formed in various different ways: in some districts they may be of sedimentary origin (Czechoslovakia), in others they may be associated with volcanic processes (Japan), and in still others they may have been formed from solutions rising from considerable depths, perhaps from the same magma chamber from which the volcanic products emerged, but after the dynamic metamorphism and the hydrothermal alteration of the ore-enclosing volcanic rocks and before the complete termination of the processes, which extended over a long time (Middle Urals).

In some provinces the deposits associated with basic and ultrabasic rocks correspond to the early stage in the development of the geosynclinal zones, whereas in others they appear repeatedly, even in the period after the folding, and their occurrence characterizes not only a definite stage of development of the mobile zone, but also a definite structural type of metallogenic zone; they are formed under the conditions of deep and repeatedly reopened faults that appear in the early stage of development of the geosynclinal region.

Particular complexes of deposits are associated with definite types of rocks. For example, differentiated hyperbasic intrusives are accompanied by chromite and nickel deposits, basic intrusives contain magmatogenic deposits of titanomagnetite, copper and vanadium ores, whereas alkaline granites and syenites – which are differentiates of the same magma in areas where limestones occur – are accompanied by magnetite and copper contact deposits of the skarn type.

On the basis of their structural position in areas of femic mineralization, one may distinguish zones of greenstone basins with pyritic mineralization, fault zones with basic and ultrabasic intrusives accompanied by complexes of associated magmatogenic and postmagmatic deposits, and zones of late acidic and alkaline products.

Ore Regions and Districts of the Sialic Type

Ore regions of the sialic type and transitional regions (with some slight occurrence of igneous activity of the early stages) occur in the folded regions of the eastern part of the USSR. Geosynclinal basins of this type extend for considerable distances, sometimes forming curvatures on the map to the extent of creating ring-shaped and arch-shaped structures around massifs in their interior (in the Yana-Kolyma regions and elsewhere).

Geosynclines of the sialic profile correspond to zones of extensive shallow basins characterized by the accumulation of thick, mainly terrigenous, rocks. The seas in these basins were for the most part shallow, as may be judged by the development of flysch-like terrigenous sequences in them. Nevertheless the prolonged subsidence led to the formation of very thick deposits. Basic extrusives of the early stages in these basins, if they occur, are relatively small in amount and in most cases are of no metallogenic interest. Sometimes zones that contain large amounts of basic extrusives contain not only granites, but also granitoids with high basic content; with these are associated not tin, but copper-molybdenum mineralization and gold (the Grodekov basin of the Primor'ye region). According to Marshall Kay's classification, these regions of terrigenous sequences may frequently be miogeosynclines. The majority of folded regions corresponding to these are characterized by a polycyclical de-

velopment of multiphase granitic intrusives. In these regions, among thick terrigenous sequences, one sometimes encounters limestones and dolomites, most often formed in zones of interior uplift. The intrusive rocks in them are primarily represented by granites. With the earlier phase of the granites are associated iron-ore deposits of the skarn formation.

Later in these folded regions there frequently appeared new basins of secondary order: intrageosynclines separated from each other by interior uplifts. In the intrageosynclines there was a new accumulation of terrigenous sequences - sandstones, clay rocks or flysch-like formations. The regions of uplift frequently did not sink beneath sea level and thus served as a source of material in the formation of the terrigenous sediments in the basins.

In the terminal period of folding in the intrageosynclinal zones there frequently appeared anticlinoria, with the injection of granitic intrusives into the terrigenous sequence. Parallel with this, in the rigid blocks of the interior uplifts, igneous rocks were formed, but under essentially different conditions: most often in fault zones and sometimes in a carbonate medium among volcanites, which exerted an important influence on the chemistry of the intrusives themselves.

In linear sialic regions one may distinguish several types of mineralization:

1) The first type consists of rare-metal zones developed in intrageosynclinal areas composed of sandstone and shale sequences. In these zones are formed massifs of acidic and hyperacidic granites, frequently intruded into the axial part of anticlinal structures and large anticlinoria. The granites themselves, and especially their late differentiates, which were formed in an aluminosilicate medium, are clearly leucocratic and rich in volatile constitutents, and represent the final differentiates of the granitic melt or else are derived from peculiar pegmatoidal melts intruded into the upper parts of the earth's crust.

In certain cases, at great depths or beneath an undisturbed and unbroken cover of sedimentary strata, are formed pegmatoid granites and vein pegmatites with a complex of rare elements (lithium, beryllium, tantalum, niobium and tin), occurring in transverse bends and horst blocks. In these cases, when the late products of magmatic differentiation, enriched in volatile constituents, are intruded into fault zones in the surficial parts of the earth's crust, they lose their volatiles and acquire contact aureoles with deposits of the quartz formation - greisens, quartz veins with cassiterites, wolframite, beryl and other rare minerals. Such deposits occur in areas of lesser vaporization, as compared with pegmatites. The deposits associated with pegmatites and quartz veins, according to their association with leucocratic granites and their content of lithophilic ore elements, may be assigned to the leucocratic group. Typical features of such deposits are: an extremely close association between the mineralization and the apical parts of granite intrusives, localization of the mineralization not far from the active magma chambers and small vertical extent, so that the mineralization does not usually spread far from the apex of the massif. On the other hand, in areas where faults occur there is also a cassiterite-sulfide mineralization which appears far from the intrusives and extends for great distances vertically.

2) Another type of ore district occurs in zones of uplift composed of limestones or volcanic rocks; these contain primarily lead-zone deposits. The lithologic and tectonic conditions of the formation of these deposits are essentially different. During the time of mineralization, the surrounding rocks usually consisted of already highly consolidated blocks, sometimes penetrated by ancient granites and renewed by later folded movements, mainly by the formation of fractures.

The young intrusives in uplift zones are for the most part discordant, and since these intrusives are developed in a medium rich in limestones or in basic and intermediate volcanic rocks, they show clear traces of hybridism and a tendency toward varieties with a high content of basic elements.

The distribution of the ore bodies associated with deep magma chambers is controlled mainly not by magmatic, but by structural, lithologic factors. The ore bodies form zones extending along belts of limestones and especially along their contact, so that their distribution depends on the shapes of their second-order and third-order folds. At the same time they are localized in systems of disruptive dislocations and quite frequently at their intersections, indicating a high degree of structural control of their distribution.

The mineralization can usually be traced to considerable depths (hundreds of meters), sometimes showing a vertical zonality in its distribution: with increasing depth there is an increase in the amount of the zinc and copper and a decrease in the amount of lead.

Such deposits are of many types. Limestones in zones of transverse uplifts at the contacts with large, and for the most part ancient, granite massifs and also in zones of intercontact faults form reaction-bimetasomatic skarn deposits. These ore bodies are often distinguished by their great thickness and great lateral extent, the mineralization also having a considerable vertical extent. A characteristic feature of the deposits of this type is

the superimposition of sulfides on fractured skarns. These sulfides, located in reaction-bimetasomatic skarns, here are late superimposed formations formed at lower temperatures than the basic skarn itself. This (if the nature of the host rocks is preserved) may explain the great vertical preservation of the mineralization. The great vertical extent of the mineralization in particular indicates that the source of the ore-bearing solutions lay at considerable depth.

At the plunges of the structures appear infiltration skarns, both at the contacts between the limestones and aluminosilicate rocks, and within the limestones where they are cut by fractures. These deposits are usually represented by pipe-like hedenbergite-sulfide bodies of complex shape, traced to considerable depths along the intersection between longitudinal and transverse fractures. Such deposits unusually characterize young metallogenic regions (the Primor'ye, Japan, Yugoslavia, etc.). The vertical extent of the mineralization in these deposits is less (on the order of 400 m), but even within this distance there is a vertical zonality, with increasing amounts of lead at depth. Characteristically the upper parts of these deposits in young metallogenic regions (Primor'ye) reached layers very close to the earth's surface (on the order of 500 m). Their roots occur at depths of many hundreds of meters (1000 m or more from the ancient surface). The active source of the ore-bearing solutions is here apparently hidden at great depth. It appears only in zones of multiphase small intrusives and extrusives in the craters of ancient volcanoes, localized in the same areas as the mineralization.

Mineralization of the more low-temperature type in limestones includes the mesothermal deposits of the Transbaykal, in which the high-temperature minerals (hedenbergite and others) are absent, and the principal accessories of the sulfides are quartz and carbonates. The structural-lithologic features of these deposits are for the most part the same as those of the skarn deposits of the infiltration type, except that the outlines of the ore bodies here are more complicated. In addition to pipe-shaped and lenticular ore occurrences, there are also ore bodies with intricate contours and knee-shaped curvatures formed as a result of the combination of steeply dipping pipes and vein-like bodies with flat-lying stratified bodies. In these bodies as well, which are far removed from the active magmatic sources, there is the same vertical zonality: the amount of galena decreases with depth and the relative amount of sphalerite increases.

In certain polymetallic deposits of tin-bearing regions one also finds tin, and in this case the deposit has the appearance of complex tin-polymetallic-cassiterite-sulfide deposits. It must be noted that when there are limestones present the cassiterite-sulfide deposits are also formed in areas characterized by a predominance of leucocratic mineralization. In every case, when the tin-bearing intrusives are injected into limestones they are accompanied by the formation of deposits rich in sulfides, which are here intruded in the cassiterite-sulfide formation.

A special group of ore-bearing districts in folded regions is represented by ore areas located in zones of marginal and superimposed faults, stretching along the edges of folded regions where they border on crystalline massifs or located at the junction between areas of uplift and subsidence. In faulted zones of this type, which form major regional faults, there are peculiar types of igneous rocks and ore deposits. In these zones are formed massifs of acidic granites accompanied by rare-metal mineralization, and in some places alkaline massifs with a complex of rare-earth and rare-metal deposits. In zones of marginal faults one also encounters deposits of gold (sometimes together with molybdenum), associated with dikes.

The fourth type of ore-bearing districts includes longitudinal zones of young faults with antimony-mercury mineralization, sometimes extending for considerable distances. Districts of this type are characterized by the regular location of the ore bodies along zones of steeply dipping faults, as well as flat-lying surfaces of separation between beds beneath an overburden of slightly permeable rocks. Since the minieralization in the deposits of this type is very far from the magmatic source, the chief ore-controlling factors here are structural-lithologic.

Ore Districts in Regions of Block-and-Trough Structure and on Rejuvenated Platforms

A different kind of distribution of the ore districts is observed on rejuvenated platforms and in regions of block-trough structure located at the intersections of major folded and faulted zones of the earth's crust. Central Europe, for example, which is a typical example of a region of block-trough structure, shows different features of the distribution of tungsten and polymetallic mineralization. These types of mineralization are combined not only physically, but also in time, sometimes being encountered in the same ore districts. They are associated with various sources of ore-bearing solutions located at different depths.

The tin-tungsten deposits of the Erzgebirge lie in an ancient crystalline block – that is, they occur under essentially different structural conditions from the tin-ore deposits of linear geosynclinal regions, although they belong to the same genetic type. These deposits are the

classic example of cassiterites quartz deposits closely associated with acidic granites – the late products of the Upper Paleozoic intrusive complex. The ore mineralization does not continue far into the intrusives, but is localized in their contact zones; according to V. M. Kreyter and V. I. Krasnikov, this indicates the nearby occurrence of the active magma chambers. On the other hand, the silver-lead-zinc mineralization in the deposits of the Freiberg mountain region, located in the same crystalline block, extends for many hundreds of meters into its depth and is associated with deeper sources of ore-bearing solutions, perhaps also being of later formation.

Thus, in ore districts of block-and-trough structure there is sometimes no physical separation between the tin-tungsten and the polymetallic mineralization, but these formations are combined in time with the occurrence of polymetallic-sulfide mineralization at a later stage and in connection with deeper ore sources than in the case of the tin and tunsten deposits of the quartz formation.

The same relationships are characteristic also of the tin-ore province of Cornwall (England), this being a classic ore district famous for its horizontal and vertical zonality.

There is also no clear separation between the lead-zinc and the polymetallic mineralization in certain districts on rejuvenated platforms, where the mineralization developed within limestones.

On platforms that have undergone dislocations and have been drawn into regions of prolonged subsidence and succeeding gentle folding, there are different regularities governing the distribution of facies than those characteristic of typical complex differentiated linear geosynclinal zones. Here the aluminosilicate rocks sometimes compose uplifts, while the zones of extensive subsidence, as is typical of syneclises as well, are characterized by the development of carbonate sequences as well as terrigenous rocks. It is these zones of subsidence, composed of carbonate sediments in the upper part of the section and of aluminosilicate sequences at the bottom, in specific tin-bearing provinces of the Pacific Ocean belt that contain the richest tin-ore deposits of the cassiterite-sulfide formation, sometimes associated with deposits of other metals – tungsten-bearing (scheelite) skarns, as well as polymetallic ore bodies.

Zones of subsidence of this type, in contrast to geosynclines and to platform syneclises, are characterized by intensive igneous activity and various endogenic mineralization, and must be distinguished as a special morphological and genetic type, for which a separate name may perhaps also be suitable. In the absence of any generally accepted term, we shall call these basins on rejuvenated platforms "synclinoidal". The study of the structures of these types, which is being carried on with particular success by Chinese geologists, is very important, since it is these basins on rejuvenated platforms that contain deposits of tin, tungsten, antimony and other metals, while the deposits themselves are of very peculiar types and the conditions of their emplacement differ from those of ore districts in geosynclinal regions.

In considering the problem of the effect of carbonate rocks on mineralization and determining their importance in the developing of tin mineralization, one must above all take account of the forms of dislocation in the carbonate rocks and the distribution of the latter in depth. In geosynclinal regions, where the carbonate rocks have been crumpled into tight folds that descend into the depths or occur in the deeper parts of the section, they affect the differentiation of the granitic magma, leading to the occurrence of granitoids with a high content of basic elements; under such conditions it is impossible to find specific tin-bearing alaskite granites. Wherever the limestones in the upper part of the section are crumpled into gentle folds, forming a cap or cover over the sedimentary sequence, and there are aluminosilicate rocks at depth, as happens in the basins on platforms, the conditions are favorable for successive differentiation and for the development of tin-bearing intrusives that are separated out during the course of deep-seated differentiation and are intruded into the carbonate rocks that are already rich in tin. Moreover wherever the massifs have solidified at small depths, the magma does not undergo any noticeable contamination, in spite of the essential difference in the chemistry of the surrounding carbonate medium. Partial assimilation of the carbonate rocks at this stage of intrusion of the granites plays a positive role, since in destroying the equilibrium of the volatile constituents it intensifies the separation of the gaseous phase and thus hastens the processes of ore formation. Limestones are a very favorable medium for the formation of tin-ore bodies, as well as ores of other metals. Among limestones, as a rule (with very few exceptions), are formed deposits of the cassiterite-sulfide formation, whereas in aluminosilicate rocks in the ore-bearing granites themselves or in terrigenous sequences, mostly the older ones underlying the limestones, there occur deposits of the cassiterite-quartz formation (quartz veins, greisens, etc.). Thus here, too, the process of mineralization depends on the medium in which it takes place.

These examples show that similar types of deposits in various structural types of ore districts occur under similar geologic conditions. A feature common to all these varied areas is the relationship between the types of ore processes and the medium in which the deep intrusive complexes are formed before the "feeding"

of the magma into the upper structural stages that are accessible to study, as well as the tectonic conditions in the deep-seated "laboratory" where there is an active assimilation of the surrounding rocks and differentiation of the granitic magma, and where the basic features of its metallogenic specialization are determined. The chemistry of the surrounding rocks has a direct or indirect effect on the metallogenic peculiarities of the ore-bearing intrusives, in some cases causing them to be enriched in ore elements such as copper, at the expense of the basic extrusives, and in other cases determining the course of the process of differentiation and separation of the various facies that are characterized by metallogenic specialization. The type of mineralization is to a considerable degree determined by the chemistry of the host rocks, as well as by the tectonic conditions existing during the period of formation of the ore-bearing intrusives and deposits (such as the association of the cassiterite-sulfide deposits with limestones on the one hand, and with zones of major disruptive dislocations that reach into the surface or near-surface strata on the other hand).

With basins on rejuvenated platforms, characterized by the development of carbonate sequences crumpled into gentle folds, are associated ore districts with polymetallic ores of the Karatau type, at some distance from the active source of the ore-bearing solutions (as in the Kara-Tau districts). Such deposits, in their structural attitudes and their morphology, are similar to ore districts of the epiplatform type with telethermal mineralization, which has been described above.

A special type of ore district consists of superimposed zones of basins with subaerial volcanic sequences. Such basins, filled with volcanic rocks, are characteristic of regions in which recent movements have taken place. They arise in the post-orogenic stage in folded zones and are also formed on platforms during the development of regional faults. Such volcanic zones are especially typical of the margins of the Pacific Ocean belt; they are also encountered in the ore provinces of the Mediterranean belt (in the Carpathians and the Transcaucasus).

The ore mineralization in these volcanic zones may be associated with the volcanic rocks themselves (antimony and mercury, gold, lead and zinc, and sometimes tin), with the hypabyssal facies of the same volcanic complexes, and, finally, with deep magmatic basins, perhaps those from which the lavas have escaped to the surface. It is probably with these deep magma chambers that are associated some polymetallic deposits, which can be traced to considerable depths and are closely interconnected in time with dikes of volcanic rocks (as in Mexico).

CONCLUSIONS

In spite of the great variety of ore-bearing areas, one may distinguish types of ore provinces, metallogenic zones and districts characterized by different histories of development and different geologic structures. In the first place, the ore-bearing territories may be divided into areas of platform and of geosynclinal types. These major structural categories are interconnected by transitional areas: ancient geosynclinal regions which have with time become attached to platforms, some of which have occasionally been rejuvenated and produced basins similar to geosynclinal troughs (parageosynclines or synclinoidal basins). Nevertheless there are radical differences between geosynclines and platform regions, on the basis of which we may consider the ore districts of these structural units separately, dividing them into different groups. Peculiar and unique features are to be found, for example, in ancient platform regions, which are characterized by processes that did not occur in later periods. The specific conditions of the mineralization on platforms makes it possible to set apart the ore districts of the platform type as a special group.

In both ancient and young ore regions two types of development have been established: femic in zones of deep faults and sialic in zones of plastic subsidence. In all the types of ore regions three principal categories of structures have been distinguished, which determine the positions of the ore zones – these are basins, uplifts and marginal faults. The metallogenic significance of these structural elements differs in regions of different natures.

The former metallogenic conception of the relationship between the nature of the mineralization and the time of its occurrence and its association with a given stage must be supplemented by this new concept of the great significance of the structural position of the ore-bearing zones: not only the time of the igneous activity and the mineralization, but also the structural disposition of the ore zones, their historical development and geologic structure also determine their metallogenic features. Mineralizations of different types may develop at the same time in neighboring zones.

Although it is longitudinal structures – uplifts, basins and marginal faults – which determine the positions of the ore zones, transverse elements – bends in the folded series, intersecting faults and so forth – control the positions of the individual ore districts, which differ in the nature of their mineralization.

The above-mentioned principal types of ore districts are characteristic of metallogenic zones of various ages, beginning with Precambrian and ending with the very latest Tertiary. In addition one may also note specific differ-

ences between metallogenic regions of different ages, indicating a directional evolution of the processes of mineralization in time. For example, we have noted that the ancient Precambrian complex has its own unique features: the basins of sedimentation at that time had a particular nature and were distributed over considerable areas. The types of sedimentary formations were also peculiar; in particular, the development of ferruginous quartzites is characteristic only of ancient periods. The crystalline rocks in ancient regions also had their own peculiarities. Here the deep zones were characterized by processes of ultrametamorphism and granitization, whereas the surficial zones were marked by the occurrence of igneous bodies in large faults in the crystalline basement. A specific feature of ancient areas is the great and widespread distribution of secondary concentrations of ore components in the form of ore-bearing molasse sequences (of the Witwatersrand), ancient weathered crusts and placer deposits.

Paleozoic regions are characterized by elongated linear orthogeosynclinal systems, which occupy extensive areas. Certain types of ore districts have a femic profile of development, manifested in places where the geosynclinal basins (eugosynclines) are disposed along deep faults in the crystalline basement.

In Mesozoic geosynclinal regions the zones of femic profile are relatively limited: massifs of basic and ultrabasic rock are localized in narrow fault zones, and their metallogenic significance is not so great.

On the other hand, in regions of young tectonic movement new structural types of ore-bearing zones may be distinguished – the extensive basins of the Verkhoyansk-Kolyma type and later superimposed volcanic zones which sometimes intersect both the platforms and the ancient folded structures along major faults in the earth's crust (such as those surrounding the Pacific Ocean belt and the Carpathians). The volcanic zones are physically associated with deposits of lead, zinc and antimony, and in places of gold or tin, while the types of deposits themselves are unique and related to the so-called near-surface ore formation.

Thus, one may speak not only of the laws governing the distribution of mineralization in space, but also of a directional evolution in time causing changes in the nature of the ore process. Against the background of this directional change, which may be traced from the most ancient to the most recent geologic period, in each cycle of development of the geosynclinal region one may note certain regularities whose development in time has been clearly indicated by Yu. A. Bilibin. These directional changes, which are common to various structural-metallogenic zones, in polyciclical regions may occur in each cycle of the geosynclinal development apart from the others, as has been shown in the example of the Caucasus by G. A. Tvalchrelidze.

In attaching great importance to the structural positions of the various ore-bearing regions, we are not thereby denying the significance of their evolution in time. Both aspects of the problem are interconnected and must be considered together. The structural types of ore districts proposed here may be indicated on small-scale metallogenic maps.

On the other hand, a study of the various structural types of ore-bearing areas makes possible a differential approach to the problem of the genesis of the deposits themselves. Ore processes of various types have been manifested in the different types of ore districts, and it is quite likely that the controversies regarding the genesis of the deposits are frequently caused by a comparison of phenomenon that actually had nothing in common. In some areas granitization and ultrametamorphism may play the essential role in the formation of the rocks and deposits, in others the most important factor may be igneous phenomena themselves, and in still others the ore deposits may be associated with deep magma chambers.

Thus, we must conclude that the ore deposits are polygenetic in nature, so that to explain their genesis in different types of ore-bearing areas we must use various hypotheses which do not exclude each other, but are actually supplementary.

This classification of the types of ore districts has shown that analysis of metallogeny requires a variegated approach, taking account of the special features not only of the major ore-bearing provinces ore zones, but also of their parts – the ore districts themselves, whose mineralization will often be controlled by their position in transverse tectonic elements, which have their own characteristic features and their own historical development. Thus, a study of the types of ore districts is one of the most important tasks in the farther development of metallogeny.

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MAFIC MINERALS IN THE DIFFERENTIAL TRAPROCK INTRUSIVES OF THE NORIL'SK REGION[1]

by

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ABSTRACT

This paper gives a description of crystal optics of olivines, clinopyroxenes and orthopyroxenes from differentiated trap intrusions of the Noril'sk region. The Fe-content of these minerals increases during differentiation from the picrite horizon up to the uppermost differentiation products. In the contaminated lower layer the Fe-content increases likewise. At the initial stages of crystallization of every rock the formation of pyroxenes high and low in Ca occurs simultaneously, but in the final stage only pyroxenes low in Ca remain stable, indicating an exhaustion of Ca in the melt. --auth. English summ.

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The differentiated intrusions of orthopyroxene gabbro-diabases in the Noril'sk region are very interesting from the standpoint of both their petrology and their ore mineralization, represented by sulfides of copper, nickel, cobalt and platinum. These are part of the hypabyssal facies of the Siberian traprock series, forming a particular type of intrusive body.

The present article presents the results of optical investigations of the igneous mafic minerals in these intrusives. The text of the article and the measurements of the optical constants of the minerals from the Noril'sk I intrusive are the work of M. N. Godlevskiy; the measurements of the optical constants of the minerals from the Mt. Chernaya and Mt. Zub intrusives were made by A. D. Bataliyev.

Determination of the composition of mafic minerals by their optical properties is of great significance in studying igneous rock complexes of platforms (Sobolev, 1936, 1937 and 1950; Woker and Poldervaart, 1950, and Wager and Deer, 1939). One of the first scientists to successfully combine the Fedorov universal stage method with a determination of refractive indices in immersion was V.S. Sobolev, who thus was the first to establish that, in the case of igneous rocks of platforms, the change in the FeO:MgO ratio completely alters the succession of mafic minerals in the Bowen (1937) reaction series. The complex structure of differentiated traprock intrusions, the frequent repetitions of the same textures and structures in different strata and different rocks necessitate a revision of the method of differential rock identification. Along with the determination of the plagioclase feldspars, one must also find the composition (the iron content) of the mafic minerals. The comparatively high fusibility of the iron components in fractional crystallization leads to a continuous increase in the FeO:MgO ratio in the later differentiates. Hence it is clear that the most accurate diagnostic feature in identifying rocks of differentiated traprocks intrusives is the composition of the mafic minerals of orthomagmatic origin.

A BRIEF PETROGRAPHIC CHARACTERIZATION OF THE INTRUSIVES

The orthopyroxene gabbro-diabases were intruded along lines of least resistance in the corresponding tectonic structures — that is, along the bedding surfaces between formations and the boundaries between suites, so that the differentiated gabbro-diabase bodies are conformable to the general stratification. They have generally irregular pipe-shaped and frequently even trough-shaped forms. The length of the intrusions varies from 5-15 km, and their width from 0.5-3 km; their thickness ranges from 100-300 m.

The differentiation of the magma was of a crystallizational and kinetic-gravitational nature. As a result, there was a formation of layered intrusives with a gradual transition from micropegmatitic rocks at the top to olivine-rich rocks at the bottom. The differentiation was accompanied by assimilation, and by the formation of contaminated and hybrid rocks both at the top and at the bottom of the intrusive.

The magma contained many volatile components that were soluble within it at high pressures. Among these components there was a considerable amount of sulfur, causing the liquation and segregation of a sulfide melt at specific critical temperatures and pressures. The force of gravity caused the sulfide to accumulate near the bottom of the intrusive.

Each of the differentiated intrusives may be divided into a number of layers, represented by one rock or another, or frequently by an alternation of different rocks. The subdivision of the intrusive into strata is based on the indica-

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[1]Translated from Femicheskiye mineraly differentsirovannykh trappovykh intruzii Noril'skogo rayona: Mineralogichesky sbornik, no. 12, pp. 196-224, Izdatelstvo L'vovskogo Universiteta, 1958.

[2]Noril'sk Complex Geologic Exploration Expedition.

TABLE 1. Composite petrographic section through the intrusives of Noril'sk I, Mt. Chernaya and Mt. Zub

Stratum	Noril'sk I Rock	Thickness in meters	Mt. Chernaya Rock	Thickness in meters	Mt. Zub Rock	Thickness in meters
A	Volcanic breccia	2.72	Acidic hybrid rocks with xenoliths in top. Diabasic hybrid rocks and diabase-pegmatite	40	Contaminated quartz-diorites	8.8
B	Hybrid rocks and diabase-pegmatites	4.67			Acidic hybrid (granitic) rocks	28.1
C	Gabbro-diorites and gabbro Gabbro-diabases with sporadic olivine (prismatic-ophitic)	21.48 3.53	Gabbro-diabases with sporadic olivine (ophitic, prismatic-ophitic and poikilophitic)	32	Interlayered quartz gabbro-diabases, gabbro-norites, quartz-olivine gabbro-norites and other rocks.	31.4
D	Ophitic olivine gabbro-diabases and norite-diabases Poikilophitic olivine gabbro-diabases and norite-diabases	35.36 23.15	Ophitic olivine gabbro-diabases and norite-diabases. Poikilophitic olivine gabbro-diabases and norite-diabases	30 50	Olivine gabbro-diabases and norite-diabases (interlayered with poikilophitic gabbro-diabases with olivine)	62.8
E	Picritic gabbro-diabases and norite-diabases (with ore)	29.48	Picritic gabbro-diabases and norite-diabases (with ore)	40	Interlayering of picritic, taxitic and olivine gabbro-diabases and norite-diabases	29.2
F	Taxitic and contact gabbro-diabases and norite-diabases (with ore)	13.99	Taxitic and contact gabbro-diabases and norite-diabases (with ore)	8		
Total		134		200		160

tions of gravitational and crystallizational fractionation. Each stratum or layer is characterized by definite magnitude of the main parameters s and a and the secondary parameters c' and a', according to A. M. Zavaritskiy (1944), and by the FeO:MgO ratio. The various different layers and individual rocks for the most part merge gradually into each other.

The following layers are distinguished:

A. A top layer of contaminated rocks.

B. A zone of leucocratic (acidic) and mesocratic hybrid rocks and diabase-pegmatites.

C. A stratum of quartz-bearing gabbros, gabbro-diorites, gabbro-diabase and norite-diabases, sometimes with olivine.

D. A layer of olivine gabbro-diabases and norite-diabases (containing olivine up to 10-25 percent).

E. A layer of picritic gabbro-diabases and norite-diabases (containing more than 25 percent olivine) with sulfide ore mineralization.

F. A basal zone of contaminated taxitic and contact gabbro-diabases and norite-diabases with sulfide mineralization.

Table 1 shows a layer-by-layer petrographic section through the three differentiated intrusives — the Noril'sk I, Mt. Chernaya and Mt. Zub intrusives — the mafic minerals of which are the object of the present investigation. The reader will find a more detailed description of these intrusives in a paper by one of the present authors (Godlevskiy, N. D.)

OLIVINES

The composition of the olivines may be determined from determination of the refractive indices ϵ and ω and the angle 2V. The optical constants were measured by the immersion

method in orientated sections with an accuracy $\pm$ 0.002. Since an increase in the FeO content of 1 percent by weight raises the refractive index of the mafic minerals by approximately 0.0025, the accuracy of the determination of the composition of the olivines by the optical constants will be $\pm$ 1 percent. As regards the angle 2V, measured on the Fedorov universal stage, this may be used to determine the composition of the olivine with an accuracy up to 5 percent, and in some cases to 2-3 percent (Sobolev, V.S., 1950).

It is clear that the composition is determined more accurately by the refractive indices than by the angle 2V. For this reason we shall use the refractive indices as the principal magnitude and the angle 2V as a control, like the birefringence ϵ-ω measured by the Berek compensator.

Winchell's (1949) graphs have been used in determining the molecular composition of the olivine by their optical constants. The use of Wager and Deer (1939) graphs in making this determination introduces no essential changes.

The optical constants of the olivines from the Noril'sk I, Mt. Chernaya and Mt. Zub intrusives are given in Tables 2, 3, and 4.

The present authors have measured the olivines from all the rocks which contained this mineral, except for certain rare fayalite pegmatites. The results are given in the tables, in the order of increasing depths of occurrence of the rocks — that is from top to bottom in the section. Graphs combining the composition and the optical constants of the olivines from all three intrusives as shown in Figures 1, 2, and 3. These clearly show the dispersion of the points for the magnitude of the angles 2V at the same value of the index ϵ.

TABLE 2. Optical properties and composition of olivines in intrusives: Noril'sk I

Number	Rock	Optical constants				Molecular composition	
		($\pm$) 2V	ϵ	ω	$\epsilon-\omega$	Fo (Mg_2SiO_4)	Fa (Fe_2SiO_4)
1	Ophitic olivine gabbro-diabases and norite-diabases	-84° -80° -82°	1.720	1.692	0.040	70	30
		-82° -84° -85° -86°	1.720	1.680	0.040	76	24
2	Poikilophitic olivine gabbro-diabases and norite-diabases	-86° -87° -89°	1.708	1.670	0.038	82	18
		$\pm 90^{\circ}$	1.704	1.668	0.036	84	16
3	Picritic gabbro-diabases and norite-diabases	$\pm 90^{\circ}$ $\pm 88^{\circ}$	1.700	1.662	0.038	86	14
		-88°	1.702	1.662	0.040	85	15
		-88°	1.709	-	-	82	18
4	Taxitic and contact gabbro-diabases and norite-diabases	-85° -87°	1.714	1.676	0.038	79	21
		-88° -86° -84°	1.726	1.688	0.038	73	27
		-84°	1.724	1.686	0.038	74	26
		-82°	1.715	1.680	0.035	79	21

TABLE 3. Optical properties and composition of olivines in intrusives: Mt. Chernaya

Number	Rock	Optical constants					Molecular composition	
		(±) 2V	ϵ	β	ω	$\epsilon-\omega$	Fo (Mg_2SiO_4)	Fa (Fe_2SiO_4)
1	Prismatic-ophitic gabbro-diabases	-82° -83°	1.736	-	1.698	0.038	68	32
2	Ophitic olivine gabbro-diabases and norite-diabases	-84° -85° -86°	1.722	-	1.684	0.038	75	25
3	Poikilophitic olivine gabbro-diabases and norite-diabases	-88° -89°	1.702	-	1.668	0.034	85	15
4	Picritic gabbro-diabases and norite-diabases	-89° +90° ∓89°	1.700	-	1.662	0.038	86	14
		-89°	1.716	1.701	-	-	78	22
5	Taxitic and contact gabbro-diabases and norite-diabases	-80° -81° -84°	-	1.726	-	-	73	27

TABLE 4. Optical properties and composition of olivines in intrusives: Mt. Zub

Number	Rock	Optical constants				Molecular composition		Remarks
		(±) 2V	ϵ	ω	$\epsilon-\omega$	Fo (Mg_2SiO_4)	Fa (Fe_2SiO_4)	
1	Olivine gabbro-norites with sporadic quartz	-80° -79°	1.744	1.706	0.038	64	36	
2	Olivine gabbro-diabase	-82° -81° -79°	1.740	1.700	0.040	67	33	
3	Olivine gabbro-norite	-84° -86°	1.724	1.688	0.036	74	26	
4	Olivine gabbro-diabase and norite-diabase	-85° -86°	1.724	1.686	0.038	75	25	
5	Picritic gabbro-diabase and norite-diabase	-89° -88°	1.706	1.668	0.038	83	17	Idiomorphic olivine
6	Picritic gabbro-diabase and norite-diabase	-81° -80°	1.742	1.704	0.038	65	35	Xenomorphic olivine
7	Picritic gabbro-diabase and norite-diabase	±90° -88°	1.702	1.666	0.036	85	15	Idiomorphic olivine
8	Picritic gabbro-diabase and norite-diabase	-80° -81° -82°	1.736	1.698	0.038	68	32	Xenomorphic olivine
9	Taxitic gabbro-diabase	-88° -86°	1.716	1.678	0.038	78	22	

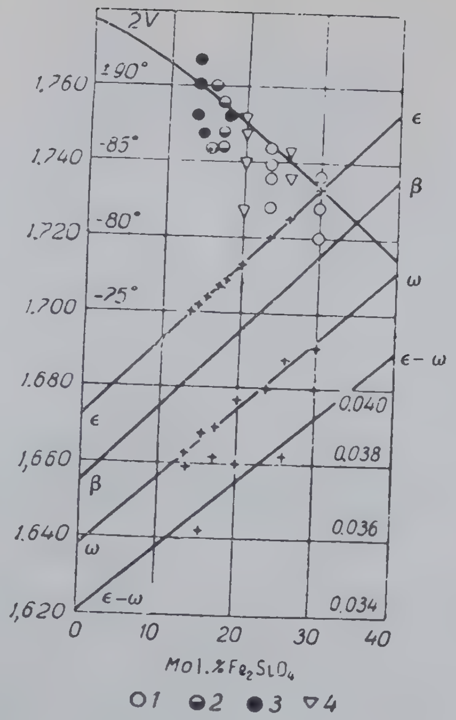

FIGURE 1. Diagram of optical properties and composition of olivines in Noril'sk intrusives (after Winchell)

1 - ophitic olivine gabbro-diabase and norite-diabase

2 - poikilophitic olivine gabbro-diabase and norite-diabase

3 - picritic gabbro-diabase and norite-diabase

4 - taxitic and contact gabbro-diabase and norite-diabase

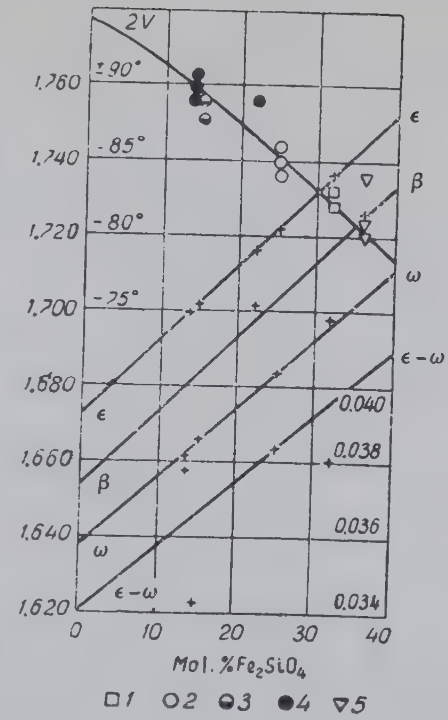

FIGURE 2. Diagram of optical properties and composition of olivines in Mt. Chernaya intrusives (after Winchell)

1 - prismatic-ophitic gabbro-diabase

2 - Ophitic olivine gabbro-diabase and norite diabase

3 - poikilophitic olivine gabbro-diabase and norite-diabase

4 - picritic gabbro-diabase and norite-diabase

5 - taxitic and contact gabbro-diabase and norite-diabase.

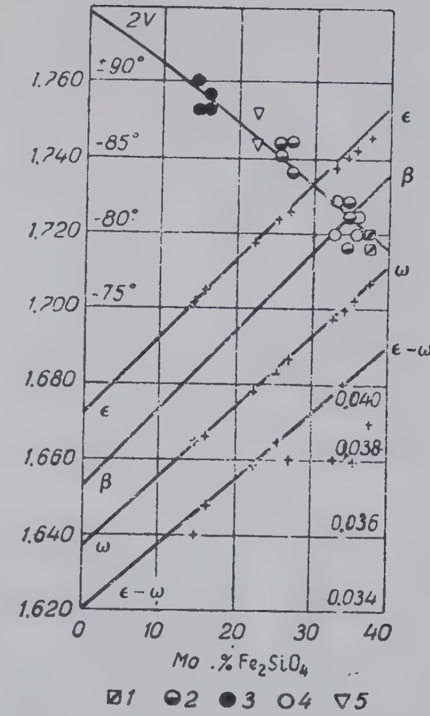

FIGURE 3. Diagram of optical properties and composition of olivines in Mt. Zub intrusives (after Winchell)

1 - quartz-olivine gabbro-norite

2 - ophitic olivine gabbro-diabase and norite-diabase

3 - picritic gabbro-diabase and norite-diabase (idiomorphic olivine)

4 - picritic gabbro-diabase and norite-diabase (xenomorphic olivine)

5 - taxitic gabbro-diabase.

The highest magnesium content of the olivines is found in the lower layers of the igneous core of the intrusives — in the picritic rocks. These are early segregations of idiomorphic or slightly fused grains varying from 0.2-2mm in size. For the most part they are resorbed small relict grains of olivine included in monoclinic pyroxene. The composition of the olivines in the picritic layers varies within fairly narrow limits: some 14-18 percent Fe, in only some cases rising above 20 percent Fe. In the Mt. Zub intrusive, which was formed under especially low-equilibrium conditions, besides the early segregations of olivine the picritic gabbro-diabases also contain xenomorphic olivine of the second generation. The composition of the latter differs sharply in the direction of a higher content of iron (32-35 percent Fe).

In the lower part of the D horizon the composition of the olivine differs little from that of the olivine in the picritic layer. But the overlying ophitic gabbro-diabase has a more ferruginous olivine containing from 24-33 percent Fe.

The rocks in the C layer were formed by crystallization of the remaining part of the magma, which was contaminated to one degree or another by material of the surrounding sedimentary rocks. In the C layer the olivine gradually disappears and quartz gradually appears. Very frequently one encounters a non-equilibrium paragenesis of quartz and olivine, but fresh olivine is never observed in direct conjunction with the quartz. In the rock of the C layer the olivine is usually found as xenomorphic grains containing up to 36 percent Fe.

In A and B, the upper layers of hybrid rocks, the olivine is encountered only rarely (in the fayalite pegmatites); as regards the layer of lower contaminated rocks, as well as the taxitic and contact gabbro-diabases and norite-diabases, olivine occurs quite frequently in these. The amount varies from 10-15 percent, but sometimes reaches 25-29 percent or even decreases to zero. The composition of the olivine in the taxitic layer is quite variable, and the shape of the grains also changes frequently, occurring as both idiomorphic and xenomorphic grains of olivine intersecting the laths of plagioclase. Fine-grained olivine also occurs within the hornblende aggregates.

Such variability in composition and form is quite characteristic of rocks which have assimilated a large amount of material from the host rocks. The contents of the fayalitic component in the olivine from the taxitic layer changes from 21 to 27 percent Fe.

MONOCLINIC PYROXENES

Monoclinic pyroxenes are encountered as xenomorphic grains in all the rocks of the differentiated intrusives. In determining the composition of the monoclinic pyroxenes the following optical constants were measured: the refractive indices ϵ and ω in immersion (in oriented sections) and the angles 2V and c:ϵ on the Fedorov universal stage. Whenever it was possible the D. S. Korzhinskiy (1928) method was used in measuring the angle c:ϵ.

Because of the complex chemistry of the monoclinic pyroxenes as multicomponent systems, determination of their composition by their optical constants generally does not produce definitive results. On the other hand, the composition of the overwhelming majority of monoclinic pyroxenes in the traprocks may be expressed quite simply by components of the 3-member system $Mg_2Si_2O_6$-$Fe_2Si_2O_6$-$Ca_2Si_2O_6$. Aluminum oxide occurs in considerably smaller quantities. For example, analysis of the monoclinic pyroxene containing small growths of plagioclase from the prismatic-ophitic gabbro-diabase of the Mt. Chernaya intrusive, as made by M. Ye. Yakovlev (1947), gives 4.24 percent Al_2O_3. Part of this aluminum oxide belongs to the plagioclase. Calculations show that the pyroxene contains no more than 2 percent of Al_2O_3. The same analysis gives 0.25 percent TiO_2. This admixture is not strikingly reflected in the optical properties of the pyroxenes.

Thus the principal components in the monoclinic pyroxenes from the differentiated intrusives are metasilicates of magnesium, calcium and iron. The region of stability for the monoclinic pyroxenes is bounded by the diopside-hedenbergite lines; pyroxenes richer in calcium are not found.

At high temperatures the monoclinic pyroxenes of the traprock probably change all of their proportions. As the temperature decreases, a field of dissolution appears and the varieties richer in calcium are separated from those which are poorer in this element. This break in miscibility is explained primarily by the great difference between the ionic radii of Mg^{2+} and Fe^{2+} on the one hand and Ca^{2+} on the other hand.

There is a great deal of confusion in modern geological literature in regard to the naming of monoclinic pyroxene. This confusion began with Hess, who called the normal pigeonites of the traprocks augites. He was quite properly opposed by Sobolev (1950), who stated that the spread of the term augite to pyroxenes that contain no aluminum oxide contradicts the classical definition of this term. The complicated isomorphic system of the pyroxenes still requires a rational classification and nomenclature; until such has been provided we should use such names for the minerals being studied as will reflect their interrelationships within the group.

Since the monoclinic pyroxenes of the traprocks form this continuous isomorphous series

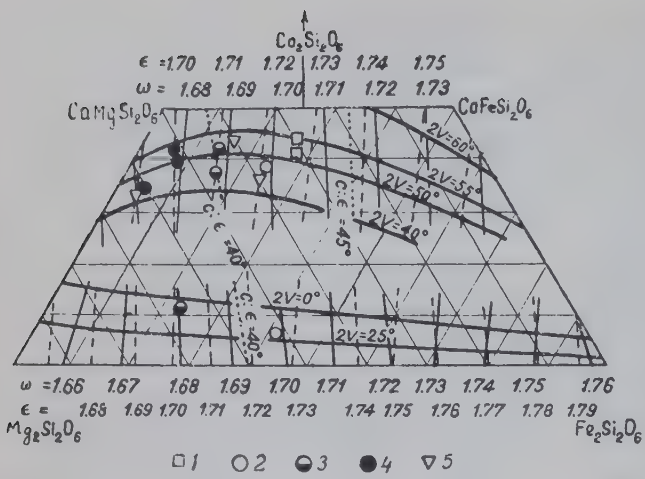

FIGURE 4. Diagram of optical properties and composition of monoclinic pyroxenes in the Noril'sk I intrusives (after Winchell)

1 - prismatic-ophitic gabbro-diabase
2 - ophitic olivine gabbro-diabase and norite-diabase
3 - poikilophitic olivine gabbro-diabase and norite-diabase
4 - picritic gabbro-diabase and norite-diabase
5 - taxitic and contact gabbro-diabase and norite-diabase.

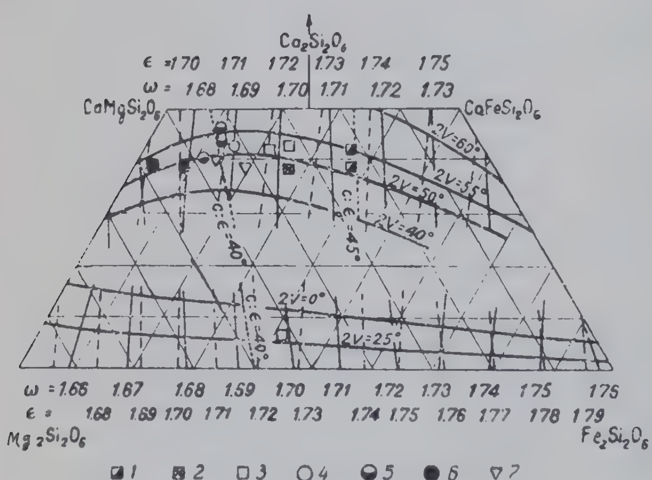

FIGURE 5. Diagram of optical properties and composition of of monoclinic pyroxenes in Mt. Chernaya intrusives (after Winchell)

1 - gabbro-diorite
2 - upper poikilophitic gabbro-diabase
3 - prismatic-ophitic gabbro-diabase
4 - ophitic olivine gabbro-diabase and norite-diabase
5 - poikilophitic olivine gabbro-diabase and norite-diabase
6 - picritic gabbro-diabase and norite-diabase
7 - taxitic and contact gabbro-diabase and norite-diabase

(although at high temperatures), we shall give them the common name of pigeonites, distinguishing two varities: 1) normal-calcic pigeonites, represented by the points in the upper parts of the "composition - properties" diagram (figs. 4, 5 and 6), and 2) subcalcic pigeonites with a small angle 2V, containing no more than 10-15 percent of the wollastonite component (the so-called Waal pyroxenes).

In determining the composition of the monoclinic pyroxenes by their optical properties we shall use the Winchell graph (1953) as the best-founded method. It should be noted that on similar graphs constructed after the method of Deer and Wager (1939) all the points are displaced somewhat in the direction of the clinoferrosilite corner of the diagram, as compared to the Winchell graph. This is especially true of the more iron-rich varieties.

The results of measurements of the optical constants of the monoclinic pyroxenes of all the three intrusives studied are shown in Tables 5, 6, and 7. The "composition-properties" diagrams (figs. 4, 5, 6) clearly show the change in composition of the monoclinic pyroxenes along the sections through the intrusives. The varieties of monoclinic pyroxenes with the highest magnesium content are contained in the picritic gabbro-diabases and norite-diabases. From this region the composition line gradually moves toward all the more ferruginous varieties, and the normal pigeonites that are richest in iron are found in the upper differentiates of the intrusives (in the gabbro-diorites and the prismatic-ophitic gabbro-diabases).

Thus the Noril'sk I intrusive shows the following range of variation in the composition of the normal calcic pigeonites:

in the picritic gabbro-diabases — $En_{60}Wo_{39}Fs_5$

in the prismatic-ophitic gabbro-diabases — $En_{30}Wo_{44}Fs_{26}$.

In the case of the Mt. Chernaya intrusive there is a similar range in composition:

in the picritic gabbro-diabases — $En_{57}Wo_{39}Fs_4$

in the prismatic-ophitic gabbro-diabases — $En_{22}Wo_{42}Fs_{36}$.

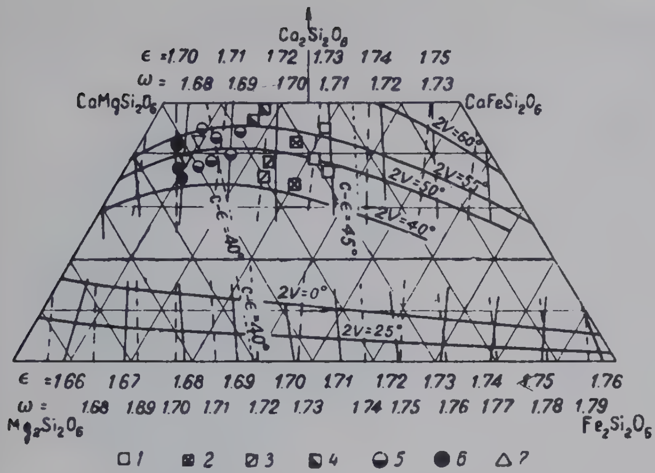

FIGURE 6. Diagram of optical properties and composition of monoclinic pyroxenes in Mt. Zub intrusives (after Winchell)

1 - gabbro-diorite
2 - gabbro-norite with quartz
3 - olivine gabbro-norite with sporadic quartz
4 - quartz gabbro-norite
5 - ophitic olivine gabbro-diabase and norite-diabase
6 - picritic gabbro-diabase and norite-diabase
7 - taxitic gabbro-diabase

It will be noted that the line representing the composition of the normal pigeonites drops somewhat toward the upper right-hand corner of the diagram — that is, the ferruginous pyroxenes contain more calcium than the properly magnesium varieties.

As regards the contaminated and hybrid rocks, measurements of their optical constants show great variations in their chemical composition. For example, in the taxitic gabbro-diabase the content of the clinoenstatite component varies from 40 to 61 percent, the wollastonite component from 34 to 46 percent and the clinoferrosilite component from 5 to 24 percent. It is clear that the range of variation in the content of the principal components of the monoclinic pyroxenes for the lower contaminates is almost the same as in the main differentiates of the intrusives. This phenomenon is quite to be expected, since in the lower taxitic gabbro-diabases one may observe a peculiar local type of micro-differentiation.

In the taxitic gabbro-diabase of

TABLE 5. Optical properties and composition of monoclinic pyroxenes in intrusives: Noril'sk I

No.	Rock	Optical Constants					Molecular Composition			Name	Remarks
		(+) 2V	ε	ω	ε—ω	c: ε	En ($Mg_2Si_2O_2$)	Wo ($Ca_2Si_2O_6$)	Fe ($Fe_2Si_2O_6$)		
1	Prismatic-ophitic gabbro-diabase	52-54°	1.726	1.702	0.024	41-44°	31-30	42-44	27-26	Normal pigeonite	-
2	Ophitic olivine gabbro-diabase and norite	20°	1.728	1.700	0.028	40°	51	7	42	Subcalcic pigeonite	Optical axis ⊥(010)
		48-49°	1.720	1.698	0.022	39-41°	38	39	23	Normal pigeonite	-
3	Poikilophitic olivine gabbro-diabase and norite-diabase	Very small	-	1.680	0.020	38°	66	12	22	Subcalcic pigeonite	Optical axis ⊥(010)
		45-50°	1.710	-	-	39-40°	46-43	38-42	16-15	Normal pigeonite	-
4	Picritic gabbro-diabase and norite-diabase	46° 50° 51°	1.692 1.700 1.700	1.672 1.680 1.668	0.020 0.020 0.032	- 35° 30-35°	60 52 53	35 40 42	5 8 7	Normal pigeonite	-
5	Taxitic and contact gabbro-diabase and norite-diabase	53° 42° 44°	1.712 1.720 1.692	1.690 1.702 1.672	0.022 0.018 0.020	42° 39-43° 38°	40 40 61	46 36 34	14 24 5	Normal pigeonite	-

TABLE 6. Optical properties and composition of monoclinic pyroxenes in intrusives: Mt. Chernaya

No.	Rock	Optical Constants					Molecular composition			Name	Remarks
		(+) 2V	ε	ω	ε-ω	c:ε	En ($Mg_2Si_2O_6$)	Wo ($Ca_2Si_2O_6$)	Fe ($Fe_2Si_2O_6$)		
1	Gabbro-diorite	52-55°	1.736	1.716	0.020	40-43°	24-22	39-42	37-36	Normal pigeonite	
2	Upper poikilophitic gabbro-diabase	48-52°	1.724	1.702	0.022	37-40°	35-33	39-42	26-25	Normal pigeonite	
3	Prismatic-ophitic-gabbro-diabase	18°	1.726	1.700	0.026	40°	52	7	41	Subcalcic pigeonite	Optical axis ⊥ (010)
		50° 52°	1.720 1.724	- 1.700	- 0.024	41° 42°	37 33	41 42	22 25	Normal pigeonite	
4	Ophitic olivine gabbro- and norite-diabase	52°	1.712	1.690	0.022	36-37°	41	43	16	Normal pigeonite	
5	Poikilophitic olivine gabbro-diabase and norite-diabase	48° 53-55°	1.704 1.708	1.682 1.688	0.022 0.029	37° 39-41°	49 43-42	40 44-46	11 13-12	Normal pigeonite	
6	Picritic gabbro-diabase and norite-diabase	48° 51°	1.700 1.694	1.678 1.771	0.022 0.023	38° 36°	53 57	38 39	9 4	Normal pigeonite	
7	Taxitic and contact gabbro-diabase and norite-diabase	47° 48°	1.716 1.708	1.694 1.684	0.022 0.024	41° 39°	41 46	39 40	20 14	Normal pigeonite	

TABLE 7. Optical properties and composition of monoclinic pyroxenes in intrusives: Mt. Zub

No.	Rock	Optical Constants					Molecular Composition			Name
		(+) 2V	ε	ω	ε-ω	c:ε	En ($Mg_2Si_2O_6$)	Wo ($Ca_2Si_2O_6$)	Fe ($Fe_2Si_2O_6$)	
1	Gabbro-diorite	48-56° 55°	1.732 1.730	1.704 1.704	0.028 0.026	46° 39-42°	29-24 30	37-44 39	34-32 31	
2	Gabbro-norite with quartz	41-52° 46°	1.726 1.728	1.700 -	0.026 -	34-40° 42°	36-31 33	34-42 36	30-27 31	
3	Olivine gabbro-norite with sporadic quartz	42-48°	1.720	1.696	0.024	34-37°	40-38	36-39	24-23	
4	Quartz gabbro-norite	59° 57°	1.718 1.716	1.696 1.692	0.022 0.024	38° 36°	34 37	49 47	17 16	
5	Olivine gabbro-diabase	48° 54°	1.712 1.714	1.690 1.690	0.022 0.024	39° 42°	43 39	40 45	17 16	Normal pigeonite
6	Olivine norite diabase	46-52°	1.708	1.686	0.022	38°	47-44	39-44	14-12	
7	Olivine gabbro-diabase	46-52°	1.704	1.680	0.024	40-41°	50-47	38-43	12-10	
8	Picritic gabbro-diabase and norite-diabase	48-52° 42-45°	1.700 1.701	1.676 1.674	0.024 0.027	37-41° 36-37°	53-51 54-53	38-42 35-37	9-7 11-10	
9	Taxitic gabbro-gabbro-diabase	48° 52°	1.702 1.704	1.680 1.682	0.022 0.022	38° 39°	51 47	39 43	10 10	

the Noril'sk I intrusive one finds polysynthetic twins of normal calcic pigeonite along the first pinacoid (fig. 7). Figure 8 shows a stereographic

FIGURE 7. Polysynthetic twin in normal pigeonite. Noril'sk I intrusive, taxitic gabbro-diabase.

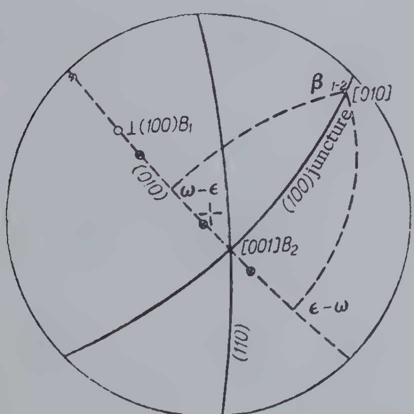

FIGURE 8. Stereographic projection of polysynthetic twin in normal pigeonite.

projection of this twinning. The twinning plane is the surface (100), and one twin axis coincides with [001], and the other is normal to (100). The optical indices are oriented in such a way that the β axes of both ellipsoids coincide, and the ϵ axis of the first ellipsoid coincides with the ω axis of the second and vice versa.

SUBCALCIC PIGEONITE

In addition to ordinary pigeonite, the intrusives studied here also contain subcalcic pigeonite (Waal pyroxene), characterized by a small angle 2V—from 0 to 20^{o}. Subcalcic pigeonite, as a mineral of essential genetic importance, has been set aside as a particular division of this article. It is developed in stratum C and in the upper part of stratum D (that is, in rocks that are relatively rich in iron). In the Mt. Chernaya intrusive, which is distinguished by the high magnesium content of its rocks, subcalcic pigeonite does not appear in stratum D.

The crystallographic properties of subcalcic pigeonite do not differ at all from those of normal pigeonite. The refractive indices show the same range of magnitudes. β and ω of subcalcic pigeonite differ little from each other, and the angle 2 V is close to 0^{o}. In the overwhelming majority of subcalcic pigeonites the optical axes are not in the plane of the second pinacoid, but normal to it. Only rarely does one encounter intermediate varieties, which are richer in calcium, and in which the plane $\epsilon\,\omega$ is parallel to (010). This change in the orientation of the plane $\epsilon\,\omega$ may be represented as follows: as the content of calcium in the pigeonite decreases, the magnitudes of β and ω approach a certain critical point at which they become equal to each other; thereupon the pigeonite becomes uniaxial (2V = 0^{o}). With a further decrease in the content of calcium β and ω exchange places, and the plane of the optical axes in the subcalcic pigeonite assumes that orientation which it has in the rhombic pyroxenes (at the "diopside" determination of the latter). The subcalcic pigeonite is distinguished in thin sections by its conoscopic appearance (but the correctness of this identification must be checked on the Fedorov universal stage).

Sobolev (1936) was the first to describe the subcalcic pigeonite in Siberian traprocks. This mineral is a quite constant component of the traprocks, but is usually omitted in petrographic investigation, so that an incorrect impression of its rareness is created. The optical constants of the subcalcic pigeonite from the intrusives described in this article are shown in Tables 5 and 6.

The subcalcic pigeonite has the following structural forms of occurrence in the rocks of the differentiated intrusives: 1) autonomic xenomorphic (ophitic) grains (fig. 9)

FIGURE 9. Subcalcic pigeonite. Mt. Chernaya intrusive, prismatic-ophitic gabbro-diabase.

2) aureoles around the normal pigeonite, and 3) close intergrowths of normal and subcalcic pigeonites, the first being replaced by the second (see fig. 13). The growth forms 2) and 3) are for the most part regular.

The autonomic grains of subcalcic pigeonite usually have the same iron content as the grains of normal pigeonite; in regard to the aureoles, they are usually more ferruginous than the grains around which they grow.

RHOMBIC PYROXENES

The presence of rhombic pyroxenes is a characteristic feature of the differentiated intrusives described there. They are encountered in all the levels without exception. In many cases the rhombic pyroxenes are present in greater number than the monoclinic varieties; such rocks are assigned to the group of norite-diabases. In the C level of the Mt. Zub intrusive there is a quartz norite, the single mafic mineral in which is rhombic pyroxene.

The nature of the pyroxene corresponds to the content of mafic lime. In the lower strata of these intrusives the deficiency in mafic lime is explained by the supersaturation of the rocks by magnesium, and in the upper strata by the excess of aluminum (as a result of melting of the clay shales).

Setting aside the problem of the actual symmetry of the rhombic pyroxenes, let us consider their optical properties. As with the other mafic minerals, the most sensitive criteria of the iron content in the rhombic pyroxenes is the magnitude of the refractive indices, among which ϵ is most accurately and easily determined. The change in the angle 2V less rigorously follows the change in composition, and the accuracy of the determination of the composition of the rhombic pyroxenes by the angle between the optical axes decreases to 10 percent (Sobolev, 1950).

In studying the optical properties of the rhombic pyroxenes, we have measured ϵ and ω in immersion, and the angles 2V and $c:\epsilon$ on the Fedorov stage, and in a number of cases the birefringence $\epsilon - \omega$. The results of these measurements of the optical constants may be seen in Tables 8, 9 and 10[3]

Note must be made of the high pleochroism of the rhombic pyroxenes from the differentiated intrusives, even in thin sections.

For determining the composition of the rhombic pyroxenes from their optical properties there are a number of suitable diagrams: those of Henry (1935), Hess and Phillips (1940), A. Poldervaart (Woker and Poldervaart, 1950), V. S. Sobolev (1950) and A. N. Winchell (1953), the results of which of which may differ quite strikingly from each other Here we shall use Sobolev's corrected graph as being the most reliable, and for the principal constant we shall use the refractive index ϵ, the magnitude of the angle 2V being plotted on the graph as a check (figs. 10, 11 and 12).

The tables and graphs show that, as in the case of the other mafic minerals, the iron content of the rhombic pyroxenes increases from bottom to top through the section, beginning with the picritic gabbro-diabases and norite-diabases.

If a content of 25 percent $FeSiO_3$ is taken as a tentative boundary between bronzite and hypersthene (Betekhtin, 1950), the bronzite will be characteristic of picritic and poikilophitic gabbro-diabases and norite-diabases. All the other rocks occurring above them will contain hypersthene. An exception will be the ophitic olivine gabbro-diabase intrusive of Mt. Chernaya, which also contains bronzite, owing no doubt to the generally high magnesium content of the rocks of Mt. Chernaya. The most ferruginous hypersthene (up to 36 percent Fs) is encountered in the upper differentiates of the intrusive, in prismatic-ophitic and upper poikilophitic gabbro-diabases, in gabbro-norites with quartz and similar rocks. Hypersthenes relatively rich in iron (28-34 percent Fs) occur in the taxitic gabbro-diabase that underlies the picritic layer.

In the C horizon of the Mt. Zub intrusive there is widespread quartz norite, consisting of bronzite (19 percent Fs), zonal plagioclase (nos. 87-47) quartz and micropegmatite. The bronzite is crystallized in the form of columns some 2-3 mm in length (for the optical properties, see table 10). This must be considered as the first generation of rhombic pyroxene, since in the rocks that are transitional between quartz norite and gabbro-diabase, this idiomorphic bronzite is replaced by monoclinic pyroxene and olivine. The appearance of a magnesium orthopyroxene in the stratum of rocks characterized by some ferruginous mafic minerals is due to the assimilation of the clay shales. The quartz norite is essentially a hybrid rock, one of the first to crystallize in the C stratum. After the complete melting of the argillite inclusions, the melt returned to its original composition by the influx of new portions of magma, and the bronzite, having become unstable, began to be replaced by ferruginous varieties of pigeonite or olivine.

Certain varieties of rhombic pyroxene, as a rule the most ferruginous ones, contain growths of monoclinic pyroxene in the form of platelets

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[3] As in the case of the monoclinic pyroxenes, the components of the rhombic pyroxenes will be tentatively designated as En and Fs.

TABLE 8. Optical properties and composition of rhombic pyroxenes in intrusives: Noril'sk I

Number	Rock	Optical constants					Molecular composition	
		(-) 2V	ϵ	ω	$\epsilon-\omega$	c: ϵ	En ($MgSiO_3$)	Fs ($FeSiO_3$)
1	Ophitic olivine gabbro-diabase and norite-diabase	66-72°	1.700	1.686	0.014	to 4°	73	27
2	Poikilophitic olivine gabbro-diabase and norite-diabase	70-76°	1.694	1.684	0.010	to 2°	77	23
3	Picritic gabbro-diabase and norite-diabase	74-79°	1.690-1.692	-	0.014	-	81-79	19-21
4	Taxitic and contact gabbro-diabase and norite-diabase	60-76°	1.704	1.692	0.012	-	68	32

TABLE 9. Optical properties and composition of rhombic pyroxenes in intrusives: Mt. Chernaya

Number	Rock	Optical constants					Molecular composition	
		(-) 2V	ϵ	ω	$\epsilon-\omega$	c: ϵ	En ($MgSiO_3$)	Fs ($FeSiO_3$)
1	Upper poikilophitic gabbro-diabase	57	1.708	1.694	0.014	to 6°	65	35
2	Ophitic olivine gabbro-diabase and norite-diabase	70-72	1.694	1.686	0.008	to 4°	77	23
3	Poikilophitic olivine gabbro-diabase and norite-diabase	72-74	1.692	1.680	0.012	to 3°	79	21
4	Picritic gabbro-diabase and norite-diabase	80-86	1.688-1.690	1.676	0.012-0.014	to 4°	82-81	18-19
5	Taxitic and contact gabbro-diabase and norite-diabase	61-63	1.700	1.688	0.012	to 3°	73	27

TABLE 10. Optical properties and composition of rhombic pyroxenes in intrusives: Mt. Zub

Number	Rock	Optical constants					Molecular composition	
		(-) 2V	ϵ	ω	$\epsilon-\omega$	c: ϵ	En ($MgSiO_3$)	Fs ($FeSiO_3$)
1	Quartz norite*	79°	1.690	1.682	0.008	-	81	19
2	Gabbro-norite with quartz	67-69°	1.702	1.690	0.012	up to 3°	71	29
3	Olivine gabbro-norite with sporadic quartz	66-70°	1.700	1.690	0.010	up to 4°	73	27
4	Quartz gabbro-norite	68-74°	1.698	1.688	0.010	up to 2°	75	25
5	Olivine gabbro-diabase	66-69°	1.696	1.684	0.012	up to 5°	76	24
6	Olivine norite-diabase	66-68°	1.696	1.686	0.010	up to 6°	76	24
7	Olivine gabbro-diabase	56-58°	1.704	1.692	0.012	up to 3°	68	32
8	Picritic gabbro-diabase and norite-diabase	70° 71°	1.694 1.692	1.684 1.680	0.010 0.012	up to 4°	77 79	23 21
9	Taxitic gabbro-diabase	52-65°	1.706	1.694	0.012	up to 5°	67	33

* According to N. A. Chernova, idiomorphic bronzite.

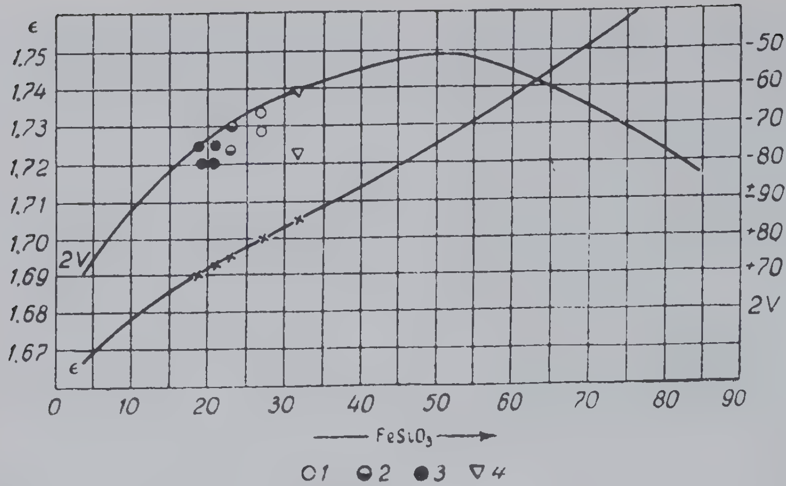

FIGURE 10. Diagram of optical properties and composition of rhombic pyroxenes using corrected curves of ϵ and 2V (after V.S. Sobolev)

Noril'sk I intrusive:
1 - ophitic olivine gabbro-diabase and norite-diabase
2 - poikilophitic olivine gabbro-diabase and norite-diabase
3 - picritic gabbro-diabase and norite-diabase
4 - taxitic and contact gabbro-diabase and norite-diabase.

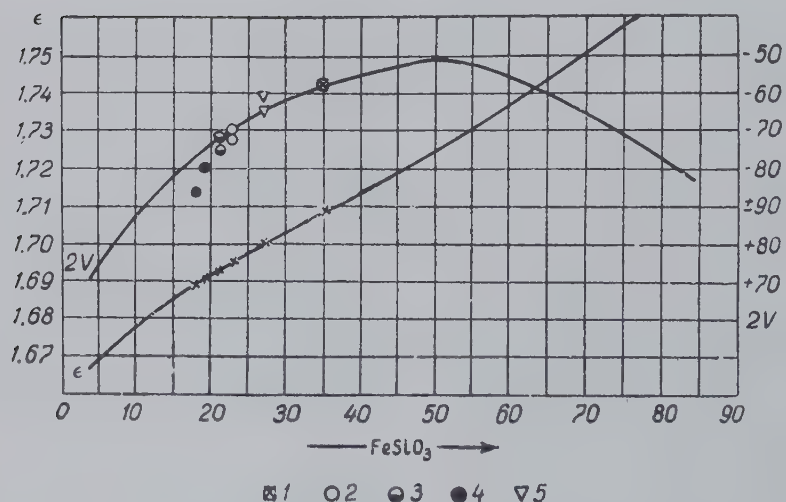

FIGURE 11. Diagram of optical properties and composition of rhombic pyroxenes using corrected curves of ϵ and 2V (after V.S. Sobolev)

Mt. Chernaya intrusive:
1 - upper poikilophitic gabbro-diabase
2 - ophitic olivine gabbro-diabase and norite-diabase
3 - poikilophitic olivine gabbro-diabase and norite-diabase
4 - picritic gabbro-diabase and norite-diabase
5 - taxitic and contact gabbro-diabase and norite diabase.

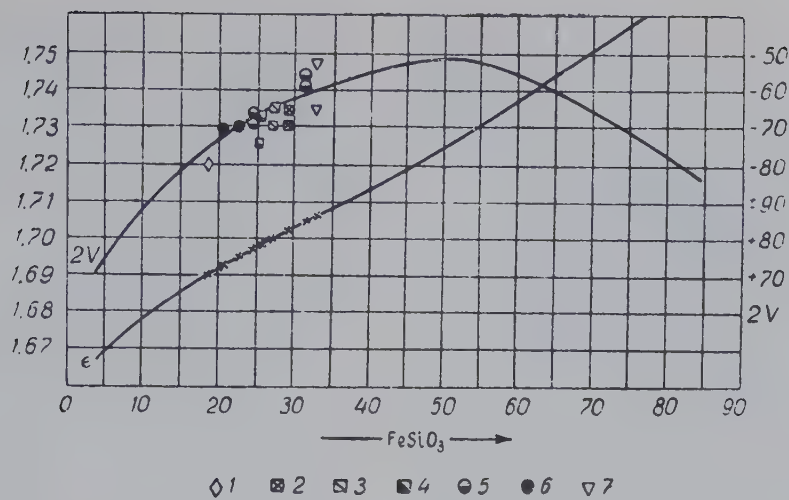

FIGURE 12. Diagram of optical properties and composition of rhombic pyroxenes using corrected curves of ϵ and 2V (after V.S. Sobolev)

Mt. Zub intrusive:
1 - quartz norite
2 - gabbro-norite with quartz
3 - olivine gabbro-norite with sporadic quartz
4 - quartz gabbro-norite
5 - ophitic olivine gabbro-diabase and norite-diabase
6 - picritic gabbro-diabase and norite-diabase
7 - taxitic gabbro-diabase.

(interlayers) and point-like emulsion inclusions. These platelets are oriented parallel to (100), perpendicular to (100) and parallel to (112). There are various views of the origin of these growths, the most likely one being that which regards this process as a melting of a solid solution (although in certain cases this is almost apparently a replacement). Structures resulting from melting are never observed in the idiomorphic grains of bronzite of the first generation from the Mt. Zub intrusive.

The rhombic pyroxenes have been found in the following forms of occurrence in the rocks of the differentiated intrusives: 1) idiomorphic grains and phenocrysts in the quartz norites of the Mt. Zub intrusive; 2) autonomic xenomorphic (ophilitic) grains; 3) aureoles around olivine where it adjoins monoclinic pyroxene; 4) aureoles around monoclinic pyroxene; and 5) complex intergrowth of rhombic pyroxene with normal pigeonite and subcalcic pigeonite, the latter being replaced by the rhombic pyroxene. The growth forms 4) and 5) are quite frequently regular.

REGULAR GROWTHS OF PYROXENES

Manifestations of epitaxis have been found in studying these growths of various pyroxenes. From the morphology of these growths it is not always possible to distinguish whether they arose by simultaneous growth or by primary replacements, meaning reactions between the earlier formed minerals and the melt. As is known (Belov, 1947), a necessary condition for the formation of regular growths is the existence in the minerals of analogous anionic nets, as is observed in this case.

The regular growths of normal and subcalcic pigeonites occurred in such a manner that the main crystallographic axes of both coincide, the optical indices also geometrically coincide and only the β and ω axes change places. Consequently, although in normal pigeonite the plane ϵ-ω coincides with the second pinacoid, in subcalcic pigeonite it is perpendicular to it. The position of the plane in subcalcic pigeonite corresponds to the same position in rhombic pyroxene, using its "diopside" determination as the criterion. In other words, the difference between subcalcic pigeonite and rhombic pyroxene in respect to the optical properties consists in the different orientations of the optical ellipsoid relative to [001].

Figure 13 shows a growth of the primary replacement type, in which the normal pigeonite (1) is replaced by subcalcic pigeonite (2), and this in turn by hypersthene (3). The direction of cleavage (110) coincides in all three minerals. Figure 14 shows a stereographic projection of this ternary regular growth. The optical indices of the two monoclinic pyroxenes are superimposed upon each other, so that $\epsilon_1 = \epsilon_2$, $\beta_1 = \omega_2$ and $\omega_1 = \beta_2$; c: ϵ = 37°; 2V of normal

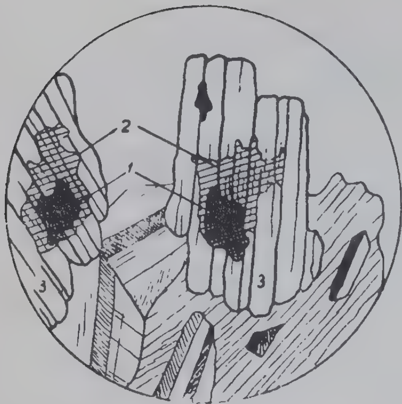

FIGURE 13. Regular growth of normal pigeonite (1), subcalcic pigeonite (2), and hypersthene (3) in primary replacement. Mt. Zub intrusive, olivine gabbro-diabase with quartz.

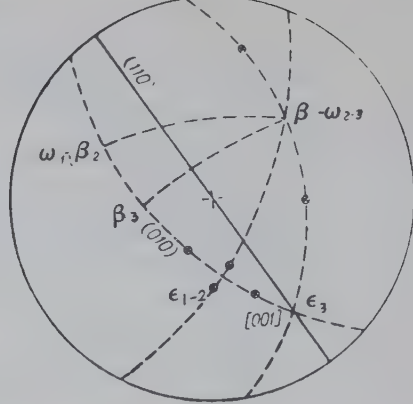

FIGURE 14. Stereographic projection of regular growth illustrated in Figure 13.

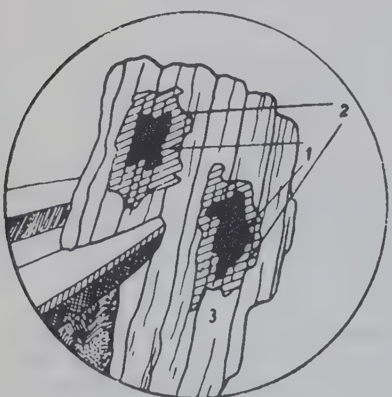

FIGURE 15. Regular growth of subcalcic pigeonite (1) and hypersthene of two generations (2) and (3) in primary replacement. Mt. Zub intrusive, olivine norite-diabase.

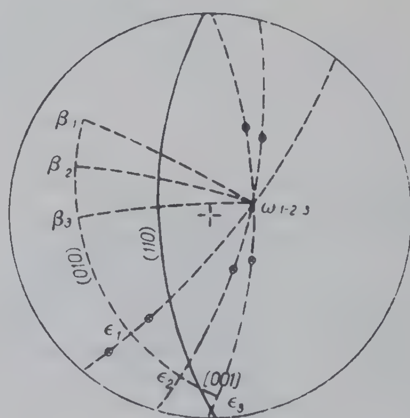

FIGURE 16. Stereographic projection of regular growth illustrated in Figure 15.

pigeonite $=+38^{\circ}$ and 2V of subcalcic pigeonite $= +12^{\circ}$. The optical indices of rhombic pyroxene are arranged in such a manner that the ω axis coincides with the ω axis of subcalcic pigeonite and the β axis of normal pigeonite, and the angle $c:\epsilon$ is close to 0°. Thus the axes $\omega_1 = \beta_2$, β_3, $\epsilon_1 = \epsilon_2$ and ϵ_3 are located in the plane $(0\bar{1}0)$, and the axes $\beta_1 = \omega_2 = \omega_3$ coincide with the plane normal to $(0\bar{1}0)$. 2V of rhombic pyroxene is $= -72^{\circ}$.

Figure 15 illustrates the other type of growth – the interrelationship of subcalcic pigeonite and hypersthene of two generations. Cores of unreplaced pigeonite lie within the grains of rhombic pyroxene, and the rhombic puroxene in its turn falls into two generations. The earlier generation of hypersthene contains regularly orientated growths of monoclinic pyroxene. This hypersthene forms aureoles around certain cores of subcalcic pigeonite. The later generation of rhombic pyroxene composes the basic mass of the grain under consideration. The hypersthene of the second generation contains no submicroscopic growths. It either directly surrounds the cores of subcalcic pigeonite or else contains these cores enclosed in a "jacket" of hypersthene of the earlier generation.

A stereographic projection of these growths is shown in Figure 16. The ω axes of all three units occur at the same point, coinciding with the plane normal to (010), and the remaining optical axes are located in the plane (010). The angle c:ϵ of subcalcic pigeonite is equal to 32°. As regards the hypersthene, in the two varieties of this mineral c:ϵ is equal respectively to 4° and 3°.

CHANGE IN THE FeO:MgO RATIO IN THE COURSE OF CRYSTALLIZATION

The crystallization of the magma and its differentiation are phenomena that occurred parallel to each other (Bowen, 1937; A. N. Zavaritskiy, 1944). Precise determination of the composition of mafic minerals by their optical constants enable us to trace the course of crystallization of individual rocks of the intrusives as a whole.

Fractional crystallization, as already mentioned, produces a certain increase in the FeO:MgO ratio in the mafic minerals as a result of the greater fusibility of the ferruginous component. Tables 11 and 12 present data on the iron content of the igneous mafic minerals from the differentiated intrusives, replacing the ratio FeO:MgO by the more suitable ratio FeO: (Fe+Mg). The increase in the iron content of the minerals is indicated by the arrows.

It follows from Tables 11 and 12 that, in the course of differentiation, the iron content of all the mafic minerals increases through the section from the picritic rocks of stratum D to the top of stratum C (as was shown earlier in describing the individual minerals). In the lower contaminated rocks, the iron content of the minerals again increases in comparison to that of the picritic layer.

As N. L. Bowen (1937) has indicated, the crystallization and development of the individual types in the rock series may have parallel courses, so that their relationships in the series are represented simply by the change in the composition of the residual melt resulting from the segregation of crystals. In our case, however, it is very difficult to determine how the iron content of the various mafic minerals changes within a single rock during the course of its crystallization, since the errors in determining the compositions by the different "composition-properties" graphs will be of different significance. Nevertheless it may be observed that, as a rule, the minerals that crystallize later have a lighter ratio of iron to magnesium.

Because of the complex genesis of these intrusives (a combination of fractional crystallization, accumulation and assimilation) there are necessarily numerous exceptions. For example, in the rocks of the picritic layer the iron content of the monoclinic pyroxenes is lower than that of the olivines, owing to the specific conditions of formation of this layer, and particularly, in contrast to the olivines, the monoclinic pyroxene of the picritic gabbro-

TABLE 11. Change in Ratio Fe: (Fe+Mg). 100 (mol.) in Mafic Minerals of Intrusives: Noril'sk and Mt. Chernaya

Intrusive	Stratum	F	E	D		C
	Rock	Taxitic gabbro-diabase	Picritic gabbro-diabase	Poikilo-phitic olivine gabbro-diabase	Ophitic olivine gabbro-diabase	Prismatic-ophitic gabbro-diabase
	Mineral	← Fe:(Fe+Mg) →				
Noril'sk I	Olivine	21-27	14-18	16-18	24-30	-
	Normal pigeonite	8-37.5	10-14	26	38	46
	Subcalcic pigeonite	-	-	25	45	-
	Rhombic pyroxene	32	19-21	23	28	-
	Olivine	27	14-22	15	25	32
Mt. Chernaya	Normal pigeonite	23-33	6-14	18-23	28	37-43
	Subcalcic pigeonite	-	-	-	-	44
	Rhombic pyroxene	28	18-19	21	23	36

TABLE 12. Change in Ratio Fe:(Fe+Mg). 100 (mol.) in Mafic Minerals of Intrusives: Mt. Zub

Stratum	E		D			C				
Rock	Taxitic gabbro-diabase	Picritic gabbro-diabase	Olivine gabbro-diabase	Olivine gabbro-norite	Olivine gabbro-diabase	Quartz gabbro-norite	Olivine gabbro-norite with quartz	Gabbro-norite with quartz	Gabbro-diorite	Quartz norite
Mineral	← Fe: (Fe+ Mg) →									
Olivine	22	15-17 (32-35)	25	26	33	-	36	-	-	-
Normal pigeonite	16-17	12-17	18-19	21-23	28-29	30-33	38	46-54	51-57	-
Subcalcic pigeonite	-	-	-	-	-	-	-	-	-	-
Rhombic pyroxene	34	21-23	32	25	25	27	28	30	-	19

diabases crystallizes in a medium with a higher concentration of magnesium resulting from the resorption of the olivine.

Sobolev (1936) and Kuno (1936) were the first to call attention to the significance of the coefficient of the iron content in the formation of the pyroxenes. Hess (1941) showed that in the case of the traprocks, the temperature of the magma at the beginning of crystallization of the intrusives lies below, and in the later stages of the crystallization lies above the temperature conversion curve of subcalcic pigeonite-rhombic pyroxene. Consequently, in magnesium-containing rocks the rhombic pyroxene is crystallized directly from the melt. In ferruginous rocks the first to be separated is the subcalcic pigeonite and only afterwards, with slow cooling, is there inversion and transformation of this mineral into rhombic pyroxene with a separation of diopside growths. In rapid cooling or in the presence of volatile components the subcalcic pigeonite is retained in a metastable state (Woker and Poldervaart, 1950; Deer and Wager, 1948). The above statements are fully applicable to the intrusives studied in this paper.

In the picritic layer, and in the Mt. Chernaya intrusive in all of the D level, there is a complete absence of subcalcic pigeonite. Here only bronzite occurs in equilibrium with the normal pigeonite. The subcalcic pigeonite occurs only in the D and C layers, where it is retained in a non-equilibrium condition, or else is replaced by hypersthene with growths of monoclinic pyroxene.

THE ROLE OF CALCIUM IN THE CRYSTALLIZATION OF THE PYROXENES

Another factor which has an equal effect on the course of crystallization of the pyroxenes is the behavior of the mafic lime or calcium.

In the differentiated intrusives of the Noril'sk region, during the initial stages of crystallization of each rock, the process followed the pattern shown in Barth's (1956) graph, the separation of calcium-rich and calcium-poor pyroxenes taking place parallel to each other: in the magnesium-containing rocks the same is true of normal pigeonite and bronzite, and in the more ferruginous rocks of normal pigeonite and subcalcic pigeonite. But in the final stages, some of the calcium-poor pyroxenes become stable, indicating a depletion of calcium in the melt. This is shown by numerous facts. For example, we see aureoles of subcalcic pigeonite around normal pigeonite, the latter showing a zonal structure: the angle +V gradully decreases from the center of the grain toward its edge (progressive zonality). N. Ye. Yakovlev (1947) cites the following example of such growth in the rocks of the Mt. Chernaya intrusive:

Normal pigeonite	Subcalcic pigeonite
$2V = 54 - 51 - 45^{\circ}$	0°

so that in both grains $c{:}\epsilon = 41^{\circ}$ — that is, the growth is regular. Thus there is a decrease in mafic calcium during the course of crystallization.

The replacement of one pyroxene by another also follows the course of a decrease in the concentration of calcium. The succession of replacements is as follows: normal pigeonite subcalcic pigeonite → hypersthene with growths of diopside → hypersthene without such growths.

In conclusion, it must be said that Sobolev's (1936) reaction series, which he has set up for the hypersthene diabases, becomes still more complicated, and instead of a double series of parallel-crystallizing mafic

minerals (olivine-monoclinic pyroxene), there appears a triple series (olivine-normal pigeonite-rhombic pyroxene or subcalcic pigeonite). The interchange of equilibrium and nonequilibrium paragenesis in both time and space is undoubtedly the main criterion of the process that bears the name of crystallization differentiation of a traprock magma. The study of these parageneses requires a thorough and accurate study of the optical properties of the rock-forming minerals, and particularly of the mafic components of the rock.

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STUDY OF ERUPTIONS AND EARTHQUAKES ORIGINATING FROM VOLCANOES (Part 2 of 3)[1]

SOME CONTRIBUTIONS TO PREDICTION OF EXPLOSIVE ERUPTIONS OF VOLCANO ASAMA,

by

Takeshi Minikami, Shirō Hirago, Sadao Uchibori and Tsutomu Miyazaki [2]

• *translated by Kinkiti Musya* •

ABSTRACT

The authors describe the equipment and methods of seismometrical observations used at Mt. Asama over the past several years. Recently, a series of telerecording seismographs have been set at the summit crater, on the flank and at the foot of the volcano and wired to the Asama Volcano Observatory, where records are taken. The setting of the transducers is given and comparisons drawn with earthquake data of Sakura-Jima, 1956-1957. The authors conclude they are similar both in type of lava and position and nature of eruption. Eruptions occurring from 1954 to 1957 are correlated with statistical data and two experimental formulas are evolved. The feasibility of volcanic-eruption forecasting is demonstrated by the first use of the formulas in forecasting —on the basis of August 1958 increases in volcanic activity – the eruption of October 3, 1958. About one month's warning was given to nearby residents and mountain climbers. The ensuing three-month period of activity had its maximum in the November 10 eruption, estimated at 10^{20} ergs kinetic energy. The authors believe their formulas may be applied to other volcanoes whose ejecta is andesitic or dacitic lava. --A. Eustus.

* * *

INTRODUCTION

In a previous paper one of the present writers discussed problems of explosive eruptions of Asama volcano and earthquakes originating from the volcano. The data were obtained by observations with a seismograph of rather low magnification (magnification 350 times, T_0 = 1 sec.) at the Asama Volcano Observatory, Tokyo University (4.2 km east of the crater) in the period 1934-1952. However, most of the earthquakes originating from Asama volcano are microearthquakes with very shallow foci. Therefore, it is essential to make observations with high-magnification seismographs set up at several points around the crater and on the flank of the volcanic cone. The writers have endeavored to develop and improve this type of observation during the past 10 years.

Observations during this period were made with the following three types of instruments: 1) A seismograph with a pendulum having a period of 1 second with its displacement amplitude magnified 4,000 to 7,000 times by means of an optical lever, 2) an electromagnetic seismograph provided with a pendulum having a period of 1 second connected to a galvanometer having a period of 0.2 seconds and sensitivity of $4\text{-}6 \times 10^{-8}$ amp. The transducers are positioned with the crater as the center. These transducers are directly connected to the galvanometer at the observatory by a sealed wire [highly insulated cable?], and thus earthquake motions are recorded at the observatory, and 3) in addition, a transducer at each station is connected with an amplifier at the observatory by a sealed wire, and earthquake motions are recorded on smoked paper. Amplifiers using both vacuum tubes and transistors are currently in use.

These seismographs, as shown in Fig. 1,

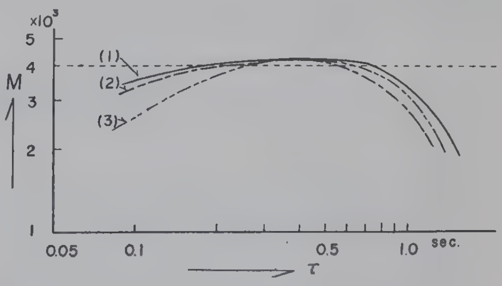

FIGURE 1. Magnifications of various seismographs used at Mt. Asama.

1 - Mechano-optical seismograph.
2 - Electro-magnetic seismograph connected to galvanometer without amplifier.
3 - Electro-magnetic seismograph connected to galvanometer through amplifier.

record the displacement amplitudes for vibration periods from 0.3 to 0.7 sec. and the magnification is adjusted to x 4,000 within the above period. Moreover, the seismographs described in (i), (ii), and (iii) are adjusted so that the instrumental characteristics coincide with one another. The instruments are tested from time to time, and their sensitivities are kept as constant as possible.

In an optical recording apparatus, time as

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[1]Translated from the Japanese in Kazan [Bulletin of the Volcanological Society of Japan], v.4, no. 2, pp. 115 to 130. Part 1 appeared in International Geology Review, v. 3, no. 8, p. 712.

[2]Earthquake Research Institute, Tokyo University.

marked every minute and every second and sometimes every 0. 2 second; instruments recording on smoked paper are timed at one minute intervals. Many records are transmitted to the observatory from a great number of transducers set at various stations, and time is recorded by the same clock, which since 1953 has been set by J. J. Y. [Tr. note: Call letters of the Electric Wave Research Institute at Koganei in the suburbs of Tokyo, broadcasting standard waves for frequency and time, day and night.]

OBSERVATIONS WITH SEISMOGRAPHS OF HIGH MAGNIFICATION

As a sequel to the previous paper, earthquakes from Asama volcano observed with the above-mentioned high-magnification seismographs for the last several years will be compared with explosive eruptions of the volcano.

1941 to 1942 and the eruptive activity of 1954 were especially noteworthy for the number of eruptions, but most were minor ones. Hence, the energy of eruption was not so great. If eruption energy is taken into account, Figure 1 in the first report [3] is obtained. As shown in Fig. 1, the activity that ranged from 1935 to 1937 was the greatest in the last 40 years, but the frequency of eruption was low.

The eruptions observed with high-magnification seismographs to December 1958 include the activity that ranged from 1954 to 1955 and the remarkable activity which began in October 1958. During this period there was quiescense from August 1955 to September 1958, when no eruption occurred. Consequently the type of earthquake occurring in the quiescent period could be differentiated from those typical of the active period. The writers were favored by this

TABLE 1. The monthly number of explosive eruptions from 1934 to 1958

Year \ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
1934	0	0	0	0	0	0	0	0	0	0	0	0	0
1935	0	1	0	8	34	6	4	23	12	3	1	2	94
1936	0	14	5	4	0	0	30	4	4	3	2	0	66
1937	0	3	13	6	1	8	0	0	0	0	0	0	31
1938	0	0	1	8	24	20	22	10	26	17	8	9	145
1939	1	17	7	11	6	6	13	5	3	2	0	0	71
1940	2	0	0	0	2	0	0	1	1	2	17	27	52
1941	95	109	21	12	18	5	11	12	13	19	21	55	391
1942	62	42	54	74	18	6	10	56	50	21	0	0	393
1943	0	0	0	0	0	0	0	0	0	0	0	0	0
1944	0	0	0	0	0	0	0	1	19	52	28	18	118
1945	22	42	19	14	3	3	6	2	0	2	3	0	116
1946	0	0	0	0	0	0	0	0	0	0	0	0	0
1947	0	0	0	0	0	0	1	1	0	0	0	0	2
1948	0	0	0	0	0	0	0	0	0	0	0	0	0
1949	0	0	20	1	0	1	4	56	41	5	0	0	128
1950	0	0	0	0	0	0	0	0	2	2	0	1	5
1951	0	1	0	1	1	0	1	0	0	0	0	0	4
1952	1	0	0	0	0	1	0	0	0	0	0	0	2
1953	0	0	0	0	0	0	0	0	0	0	0	13	13
1954	85	76	38	25	34	25	24	12	1	0	3	1	324
1955	1	2	2	24	10	45	1	0	0	0	0	0	85
1956	0	0	0	0	0	0	0	0	0	0	0	0	0
1957	0	0	0	0	0	0	0	0	0	0	0	0	0
1958	0	0	0	0	0	0	0	0	0	20	84	74	178

The monthly frequency of explosive eruptions given in Table 1 show the activity of Asama Volcano for about the last 25 years. At this point it is considered necessary for the writers to define eruptions. It is needless to say that outbursts ejecting lava blocks and volcanic bombs are eruptions, but in addition the writers include as eruption all activities discharging solid materials, even if the ejecta is only volcanic ash. Consequently the determined magnitude of volcanic activities depends on whether the number of eruptions or the energy of these eruptions is taken as the measure of the activity. In Table 1, the eruptive activity ranging from

golden opportunity to make detailed comparison of the frequency of earthquakes and the nature of earthquake motions in the quiescent period with those of active periods. In this paper, the explosive eruptions and earthquakes that ranged from October 1954 to 1958 will be described first, and then the two phenomena during and after October 1958 will be outlined.

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[3]Part I of 3: see International. Geol. Rev. August 1961, v. 3, no. 8, p. 712.

The earthquake motions from the volcano discussed in this paper were transmitted to the Asama Volcano Observatory (4. 2 km east of the crater) from transducers set up mainly at the following 3 points.

Station	Place name	Distance from the crater	Altitude
No. I	Higashi-maekake	0. 9 km	2, 350 m
No. II	Sanno-torii	2. 5 km	1, 780 m
No. III	Nakano-sawa	3. 9 km	1, 380 m

The stations No. I and No. II were situated on deposits of the most recent ejecta from Asama volcano; localities were selected where the near-surface geology was similar (fig. 2.)

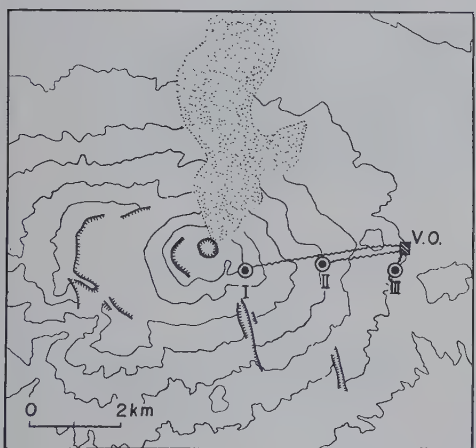

FIGURE 2. Topographic map of Volcano Asama and position of transducers

Outline of Observations from October 1956 to May 1958

In order to clarify the earthquake frequency and explosive eruptions in the above period and the earthquake frequency in the quiescent period, the daily frequency at stations No. I and No. II (n_I, n_{II}) is shown in Figure 3 and Figure 4. In the two charts the phenomena described in the previous paper based on observations since 1934 with a seismograph of low magnification are more distinctly detected. At the risk of tedious repetition, the earthquake frequency and the occurrences of explosive eruptions will be discussed statistically, based on the materials shown in Figure 3 and Figure 4.

Representing the daily frequency of earthquakes at each station (No. I and No. II) by n_I and n_{II} respectively, the 5-day sum of daily frequency at each station was prepared throughout the period (Oct., 1954 - May 1958). That is, at station No. I

$$n_{I,1} + n_{I,2} + n_{I,3} + n_{I,4} + n_{I,5} = N_{I,5}$$

$$n_{I,2} + n_{I,3} + n_{I,4} + n_{I,5} + n_{I,6} = N_{I,6}$$

. . . . . .

As before, the sum $N_{I,m}$ of earthquakes for every 5 days is obtained. Similarly, the sum $N_{II,m}$ is obtained for station No. II. Thus the frequency distribution of N at these 2 stations is represented by the curve F_o in Figure 5. Next, the frequency distribution of the group N' which consists of N for every 5 days from 2 to 6 days before explosive eruptions in this period is represented by F_o' in Figure 5. These are the same operations described in the paper when a seismograph of low magnification was employed.

The mean value and the standard deviation of N and N' observed at each station in the above period are as follows:

Station	Mean value of N (h)	Standard deviation of N (σ)	Mean value of N' (h')	Standard deviation of N' (σ')
No. I	167	18. 30	458	19. 39
No. II	129	14. 49	361	15. 33

From the ratio of the frequency distribution of N' to that of N, a curve indicating a vulnerability ratio of an explosive eruption is obtained which is serviceable in forecasting the danger of an eruption. This curve indicates a vulnerability ratio of an explosive eruption within 5 days, or, 2-6 days after a certain day by the value of N corresponding to that certain day. This curve is shown in Figure 6.

For example, in the case that the values of $N_{I,m}$ (Higashi-maekake and $N_{II,m}$ (Sanno-torii) on the day m are less than 100 a vulnerability ratio of an explosive eruption in 5 days between (m + 2)th day and (m + 6)th day is extremely low; in the case that the values of N_I and N_{II} are > 100 - < 200 a vulnerability ratio of eruption is 2 - 3 percent; and in the case that the values exceed 400, the vulnerability ratio is very high. Consequently there is good reason to believe that the above-mentioned method is effective for precise forecasting of an explosive eruption which will occur within 5 days by making use of observations to the previous day.

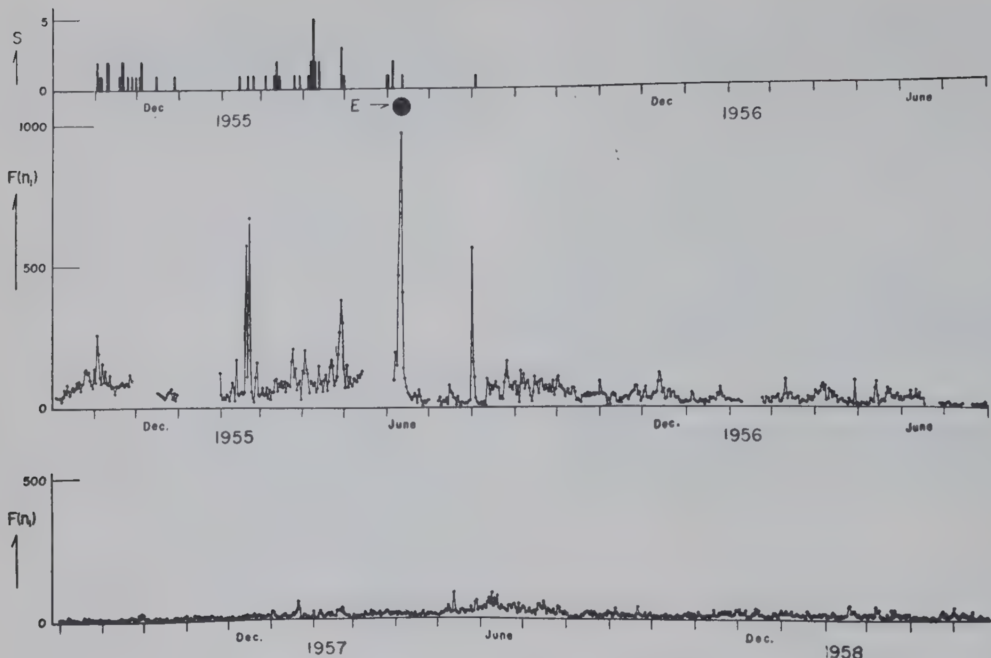

FIGURE 3. Daily frequency (Fn_I) of earthquakes originating from the volcano and explosive eruptions during the period from October 1954 to May 1958 (Transducer No. I)
S - Daily frequency of explosive eruption including very small ones.
E - Strong eruption of 5×10^{18} ergs in its kinetic energy (June 11, 1955).

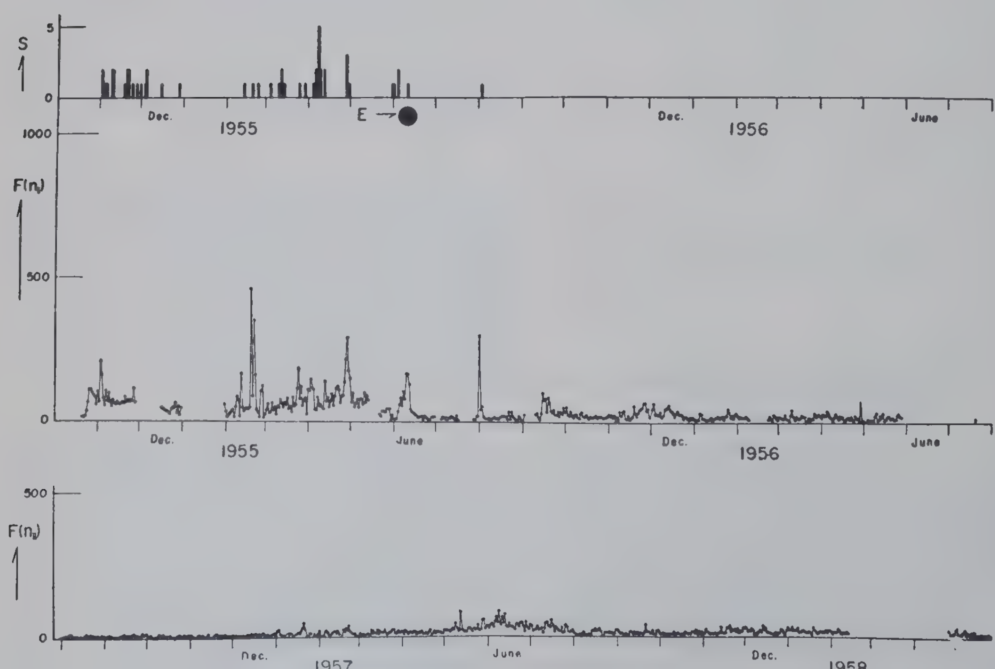

FIGURE 4. Daily frequency (Fn_{II}) of earthquakes originating from the volcano and explosive eruptions during the period from October 1954 to May 1958 (Transducer No. II)
S - Daily frequency of explosive eruption including very small ones.
E - Strong eruption of 5×10^{18} ergs in its kinetic energy (June 11, 1955).

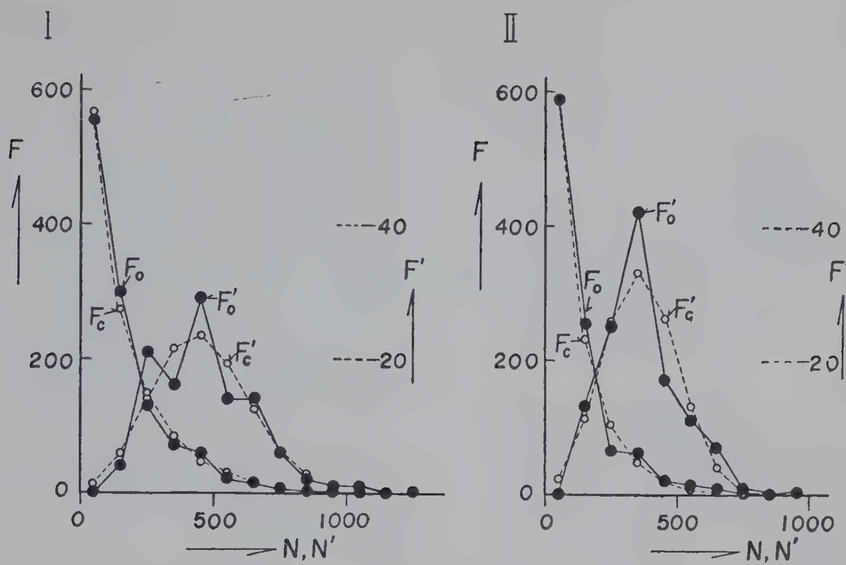

FIGURE 5. The frequency distributions of N and N' during the period from October 1954 to May 1958.

F - Frequency of N for the period.
F' - Frequency of N corresponding to the five days before respective eruption which occured during the period mentioned above, i.e. N'.
Fo, Fo' - given from observation.
Fc, Fc' - given from calculation based on the Polya-Eggenberger's distribution.
Graph I and II - given from transducer No. I and No. II.

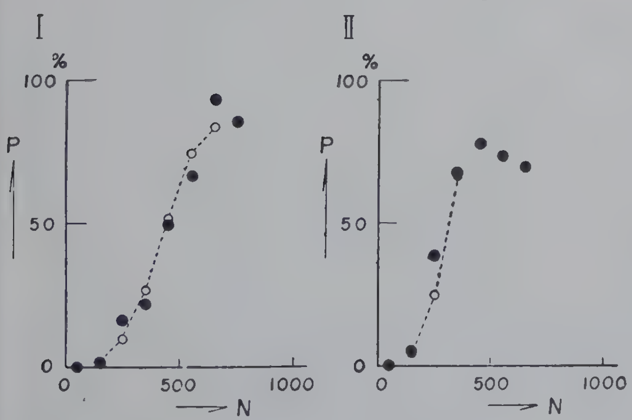

FIGURE 6. The probability of occurrence of respective eruption, based on the frequency of earthquakes originating from Volcano Asama and its explosive eruptions for the period from Oct., 1954 to May 1958.

N - Seismic frequency for five days.
P - Probability of occurrence of eruption within next five days.
o - from the calculation based on Polya-Eggenberger's distribution.
● - from the observation.
(I), (II) - by observations by the transducers Nos. I and II.

Data of the Explosive Eruptions During and After October 1958

Volcano Asama had remained quiescent for more than three years from August 1955. During this period not even a minor eruption took place. Then the volcano burst into fresh activity on October 3, 1958, and after that, successive explosive eruptions occurred. The eruption which took place at about 20 hr 50 min on November 10 was unusually violent. This eruption was of the highest order, and its kinetic energy was estimated at 10^{20} ergs. The severity of the explosion can be judged from the heavy damage to window panes from the wind blast in Karuizawa-machi and its surroundings. The explosive eruptions on December 4, 5, and 14 which followed the above outburst were also remarkable, and the kinetic energy was estimated at 10^{18} - 10^{19} ergs. Explosive eruptions inferior in magnitude to the above outbursts totalled about 178 by the end of December. Considering the magnitude of volcanic activities during the last 50 years, it is significant that this activity was next in magnitude to the violent activities of 1909-1913 and 1935-1942. These explosions were recorded on magnetic

tapes with a sterecorder at the Asama Volcano Observatory. On the one hand, comparing these records with the result of observation of earthquake motion which accompanied these explosions opened a new phase of study. On the other hand, data contributing to the solution of problems concerning the mechanism of explosion were obtained. These will be reported later. However, of greater concern to the writers was the mode of earthquake occurrence in these cases, the way the pre-eruption earthquakes appeared, and the question of whether or not the past statistical results were in conformity with the present activity and would contribute to the prediction of such eruptions. Hence, this problem will be discussed first.

The features may be grasped roughly in Figure 7, which shows the relation between the daily frequency of earthquakes which originated from the volcano and were observed at the stations No. I and No. II from January to December 1958 and the explosive activity after October 1958. Underground station No. I and the transducers set up in it were completely destroyed by a shower of large and small ejecta. Fortunately earthquakes were well recorded before the station was demolished, but after that, observation became impossible, and the writers were obliged to discontinue observation for some time. It was indeed fortunate that the transducers were brought into full play up to the fall of ejecta, thereby obtaining important records

In addition, several volcanic bombs fell on and smashed the roof of station No. II. Fortunately the transducers suffered little damage and, after a half-day delay, observation was resumed. From that time on, the mode of earthquake occurrence was observed without interruption. Station No. III suffered no damage at all and records were obtained continuously.

The daily frequency of microearthquakes recorded by the transducers at the above three stations in the quiescent period was about 20 at station No. I, 16 at No. II, and 6 at No. III. However, the frequency increased to about 3 or 4 times that in the quiescent period from August 1958 and more than 10 times in the latter part of September. In other words, the daily frequency of microearthquakes increased to 800 at stations No. I and No. II. Thus, the probability of an explosive eruption became very high, and the first explosive eruption of the 1958 activity occurred on October 3. That is, seismic activity in the interior of the volcano of about two months duration preceded the eruption on the earth's surface. The increase of seismic frequency about two months prior to the first explosive eruption was very noticeable, as was expected by the writers.

As shown in Figure 7, the pre-eruption phenomena were very remarkable. At first thought, it seems that by observation of these phenomena, the problem of predicting eruptions and preventing disasters caused by them could be solved easily. However, the writers cannot but admit that their foresight for natural phenomena is very poor. In the present case also the writers were obliged to rely upon past statistical results. In addition, the number of persons who climb Asama volcano has increased each summer. If an explosive eruption were to take place at such a time, it is clear that there might be many victims. The problem not only concerns Asama volcano but also every country with volcanoes which display violent activity. It is urged that the problem of predicting eruptions be solved as early as possible in order to remove uneasiness of people living at the foot of volcanoes and to minimize disaster in case of emergency.

From the historical point of view, it cannot be overlooked that studies of Asama volcano have been firmly founded toward the above-mentioned goal.

As a result of extensive studies, the problem of predicting eruptions from Asama volcano is nearing solution in some respects, but, on the other hand, many questions remain unsolved. However, the writers who have studied this problem cannot shut their eyes to the many climbers who crowd the crater area. Moreover, from the scientific standpoint, it is reasonable to consider that public prediction of eruption can be made only when the results obtained by the study up to the present time are applied to future eruptions and the result is confirmed as useful. The writers, who are the staff members of a research institute attached to a university, are at no time authorized or responsible for making predictions or forewarning to the general public. Nevertheless, as described above, it is intolerable for the writers to feign ignorance in the face of eruption symptoms. Indeed, the writers were in a dilemma for one to two months before that eruption. However, the Japan Meteorological Agency and the weather station near the volcano had earnestly requested us to supply them with eruption forecasts. The curve obtained at station No. I indicating the approach of an explosive eruption (I) and the frequency of microearthquakes observed at the station were supplied to the weather station every day from July 1. Thus a trial warning of an explosive eruption was given, even though the method had not been perfected.

The writers presented a tentative plan for eruption warning on the basis of frequency of B-type earthquakes as previously described in the following four stages: (1) when the value of N_I is less than 150, there is almost no danger of eruption, (2) when the value is 150-400, rather dangerous, (3) when the value exceeds 400, there is great danger, and (4) when the value is greater than 1,000, the probability of explosion is extremely large and an explosive

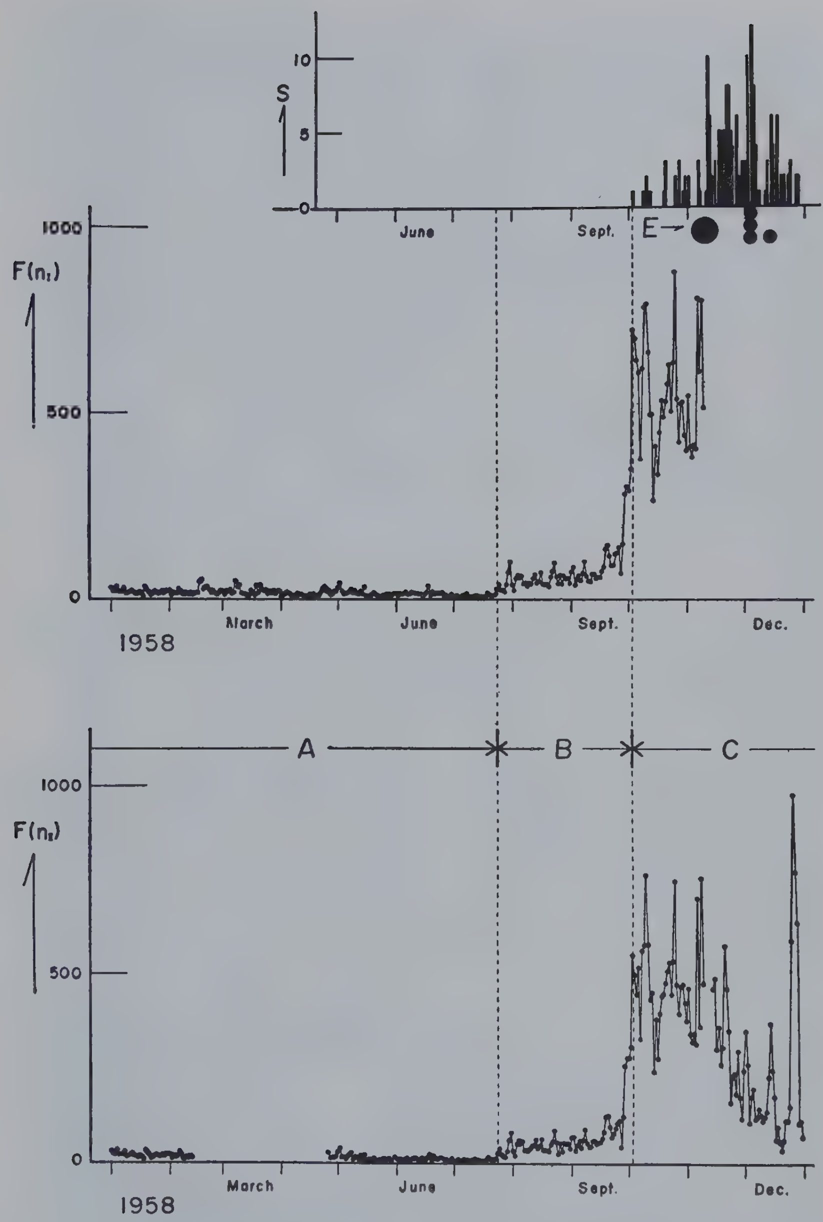

FIGURE 7. Daily frequency of earthquakes originating from Mt. Asama and the 1958 (Oct.-Dec.) eruption after its quiescence of 3.3 years.

A - Calm stage.
B - Pre-volcanic or pre-eruptive stage.
C - Stage of paroxysmal eruption.
S - Daily frequency of small eruption with fine ejecta.
E - Violent eruption ejecting lava blocks and volcanic bombs. Larger black dot indicating stronger one than 10^{19} ergs.
$F(n_I)$ - Daily frequency of earthquakes by the transducer No. I.
$F(n_{II})$ - Daily frequency of earthquakes by the transducer No. II.

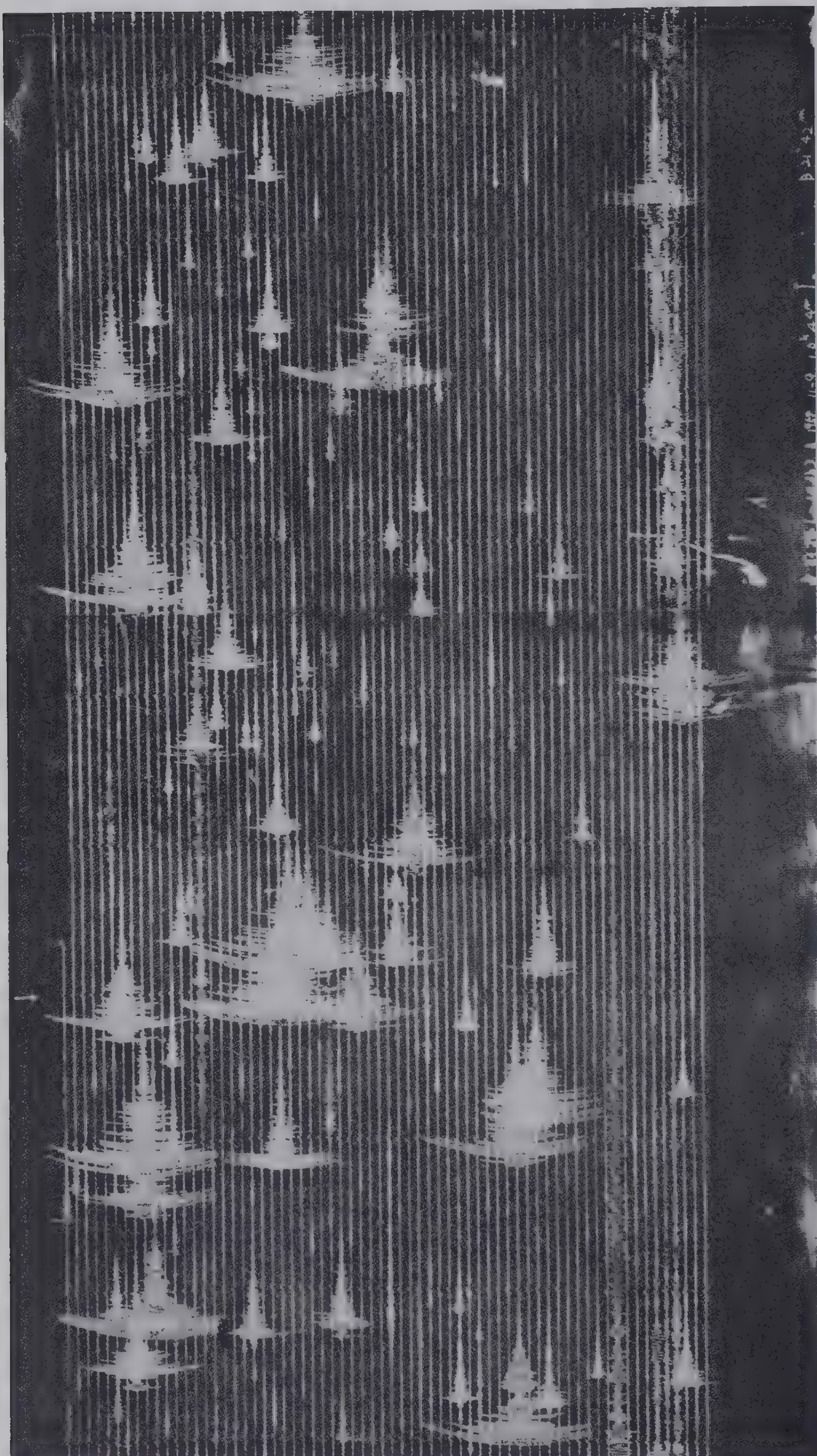

FIGURE 8. The remarkable swarm of earthquakes which took place from 10 hr 44 min, to 21 hr 42 min, November 9, 1958, i.e. from 36 hours to 25 hours before the violent explosive eruption at 22 hr 51 min, November 10, 1958, obtained by the transducer No. 1)

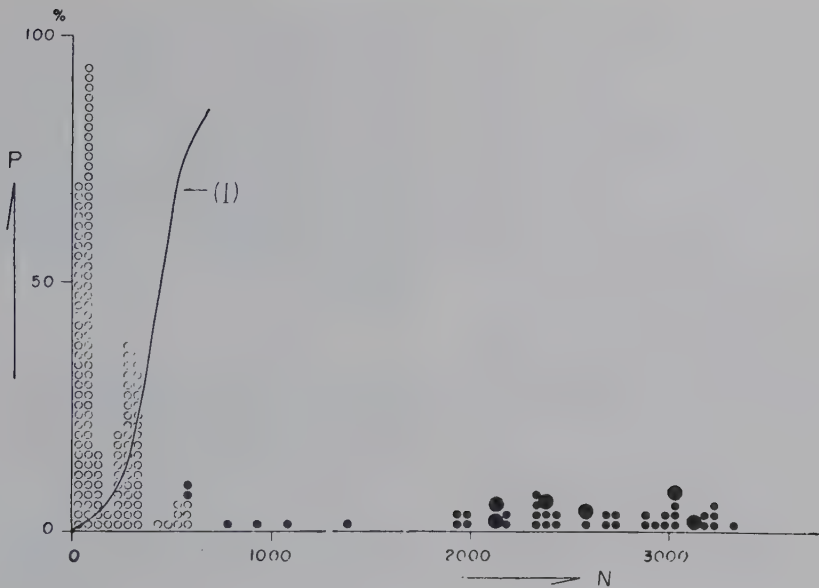

FIGURE 9. An example of practical application of the probability curve (I) to prediction of explosive eruption for the period from May to December 1958.

o - indicates the value of N which was not followed by eruption within five days.
● - indicates the value of N which was followed by eruption within five days, and its diameter represents the magnitude of eruption.

eruption strong enough to destroy window-panes of houses at the foot of the volcano may occur. The warning system put into practice by the Karuizawa Weather Station was somewhat simplified, but it was nearly the same as the writers' proposal.

In order to examine to what degree the writers' prediction conformed with N_I from May 1958 to the end of December 1958 and with the probability curve I which had been obtained previously, N_I of every day is plotted on the abscissa in Figure 9. Open circles indicate N when no eruption occurred in a period (m + 2)th day - (m + 6)th day for the value of N (Nm) of mth day; solid dots indicate N when explosive eruption occurred. As is evident in this graph, when the value of N_I was less than 550 no eruption took place, but explosive eruptions occurred when the value exceeded 550. From the beginning of August the value of N was more than 200 on most days, and to some extent began to indicate a coming eruption. During and after September the vulnerability ratio of explosion became much higher. It is particularly noteworthy that the value of N_I exceeded 1,000 from 2 - 6 days before the great outburst. At any rate, it was extremely gratifying that the present volcanic activity not only could be predicted to a somewhat satisfactory degree but also that considerable damage could be prevented by a timely warning given by the local prefectural office.

Recollection of a prediction of the present explosive eruption (1958) and measures taken on the occasion

It was very fortunate that the proper measures against volcanic eruption and subsequent disaster were taken, based on the increase of vulnerability ratio about 2 months before the present activity. The writers believe at present that the most effective method of warning against explosive eruptions of Asama volcano is to observe microearthquakes originating from the vicinity of the crater and to infer future eruptions on the basis of the earthquake frequency. However, the writers do not think that this is sufficient. Taking into consideration not only the frequency of microearthquakes but also the locations and depths of the hypocenters and also the magnitude of these earthquakes, the relation between these and eruptions must be expressed in a simple form. The writers are making efforts in this direction.

Practically speaking, it is difficult to predict the first explosive eruption in an active period and to prevent disasters on the basis of the daily frequency of microearthquakes (fig. 10). It is hoped that future study will enable precise, short-notice warnings to be made, for example, in the case of the present activity, to prohibit climbing about one week before the first explo-

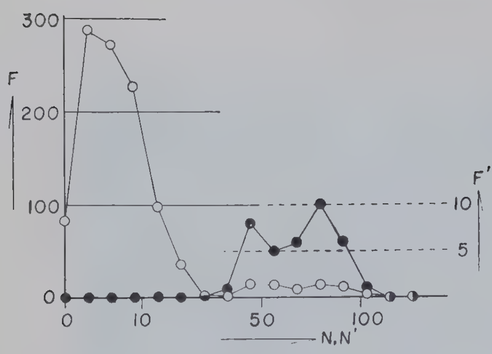

FIGURE 10. Frequency distributions (F, F') of N and N'.

N - Seismic frequency for every ten days during the period from Jan. 1956 to Dec. 1958. (o)
N' - Seismic frequency for every ten days preceding a respective eruption during the same period. (•)

sive eruption (Oct. 3). However, due to the present stage of our knowledge, it was inevitable in the case of the present activity to have given premature warning in August about a coming eruption and to have prohibited people from going within 2 or 3 km. of the crater from early September.

In the last 50 years, it has been very rare for Asama volcano to be dormant for three years, as it was in the period beginning in July 1955. When activity revives after rather long repose (more than one year), the frequency of pre-eruption earthquakes seems, in many cases, to increase about 1 to 2 months before explosive activity. If the time lag between the first explosive eruption and the abrupt increase of earthquakes is found to be constant or almost constant, it will doubtless prove highly effective for predicting eruptions and preventing disaster. At any rate, as observations continue, a law relating both phenomena will be established.

Periodical analysis of the past eruptions of Asama Volcano published by Sekiya (1959, also Sekiya and Hirano, personal and press communications) of the Karuizawa Weather Station is highly interesting. However, though he claims to have predicted eruptions with his method, the writers were unable to detect any periodicity in the eruptions of Asama. Therefore, it is practically impossible to predict eruptions and to take measures for disaster prevention based only on the periodic occurrence of eruptions. A similar situation exists concerning the prediction of great earthquakes.

In the previous paper the relation between the occurrence of eruptions and the frequency of earthquakes was discussed by almost the same method, using a seismograph magnification of 350. It is necessary to investigate whether the vulnerability ratio (or safety ratio) of eruption obtained above is applicable in any way to subsequent eruptions. Figure 11 shows the probability curve (I) obtained from the observations in 1953 and the probability curve (II) obtained by the same method in a period including the activity in October-December, 1958. It is evident that the characteristics of both periods almost coincide with each other, i. e., that the prediction of an explosive eruption using curve (I) was possible.

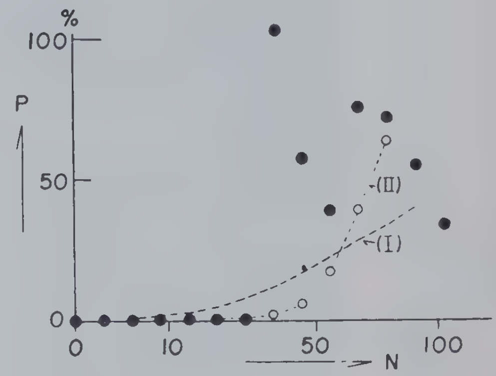

FIGURE 11. Comparison of the probability curve which was obtained in 1953, with that obtained from observations of earthquakes and eruptions during the period from Jan. 1956 to Dec. 1958.

(I) - the 1953 probability curve
(II) - the 1958 probability curve
• given from observation during 1956~1958.
(i.e. (100xF')F in Fig.10)

The relation between the explosive eruptions of Asama volcano and earthquakes which originate from the volcano was discussed previously. All earthquakes which originate from the volcanic body of Asama were treated as equal factors and the changes in seismic frequency alone were considered. Most of these earthquakes originated from a very shallow depth beneath the summit crater. The hypocenters of these earthquakes will be discussed in some detail later.

ON THE PREDICTION OF ERUPTIONS AND THE PREVENTION OF DISASTER DUE TO ERUPTIONS

Great damage is sometimes caused by volcanic eruptions. To say nothing of the catastrophe of Pompeii due to the eruption of Vesuvius, it is illustrated by the outbursts of Asama in 1783 (Omori 1912-1914; Yagi, no date) Krakatoa in 1883, (Krakatoa Committee 1888), Pelee in 1902 (Lacroix, 1904), Keloed in 1919 (Kem-

merling, 1921) Hibok-Hibok in 1948-1951, (Alcaraz et al., 1952 a and b) Lamington in 1951 (Taylor, 1958) Bezymianny in 1956 (Gorchkov, 1959), etc. Hence, workers in Japan and in many countries throughout the world are making concerted efforts to solve the problem of prevention of disaster due to volcanic eruptions. This problem was a principal subject of discussion at the International Volcanological Symposium held in Paris in September 1959. In addition, the possibility of utilizing the energy of volcanic eruptions is also held as one of the goals of volcanology.

However, even if the study is limited to the problem of eruption prediction and disaster prevention, a straight forward solution is not always possible. The problem of disaster due to volcanic eruptions must be studied from at least two points of view. One is the damage to life and property of inhabitants at the foot of a volcano. The other is the damage to life and property because many climbers crowd the vicinity of the crater. Moreover, various conveniences for climbers have been constructed near the crater itself as a result of the measured popularity of sightseeing. The above two considerations are considerably different from the standpoint of eruption prediction and disaster prevention, though the cause is one and the same. The latter is a particularly difficult problem. When many people are crowded near the very narrow crater rim, it is highly probable that heavy casualties would be caused instantly, even in case of a minor eruption. Therefore, a perfectly trustworthy prediction is required in this case. On the other hand, in the former case it is sufficient if only an eruption of relatively large magnitude is predicted. Moreover, there is time lag between the occurrence of an explosive eruption and disaster caused by the eruption at the foot of the volcano. Therefore, disaster prevention in this case is easier than in the case of the climbers.

As seen from the eruptions of Miyake-shima, Sakura-jima, Usu-san where actual eruption can occur from many possible vents, prediction of eruption location also becomes an important problem. This problem will be discussed again at a later date.

CONCLUSION

This paper reports that the remarkable volcanic activity of Asama volcano that began in October 1958 was predicted by making use of the statistical relation between the 1954-1955 eruption and the mode of earthquakes prior to the 1958 eruption. Observations were made with seismographs of high magnification during and after 1954. The writers in cooperation with the Karuizawa Weather Station, gave an eruption forecast and took measures for disaster prevention. The results were fairly successful. The 1958 activity of Asama volcano occurred after a quiescent period lasting more than three years. Probably because of this pre-eruption earthquakes appeared distinctly more than two months prior to the first explosive eruption. Consequently, warning of an eruption was given too early. This was inevitable in the present stage of our knowledge. The writers may have dwelled too long on the prediction of eruptions and the prevention of disaster. However, it was quite natural, because the principal purpose of this paper is to emphasize that it is all the writers could do even in Asama volcano, which in this report is the most studied volcano in Japan. The writers ask a criticism on the study.

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[Part 3 of 3 will appear in a subsequent issue of International Geology Review].

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A major function of the AGI translations program is the screening of foreign literature for material that should be made available to the English-speaking scientist. Researchers who need such material are urged to review these lists and send us their recommendations for consideration by the editors; the translation needs of all geologists will be served better thereby.

-- Managing Editor

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Lithology of Cretaceous sediments in the Chay-Tumus coal deposit (left bank of Lena Delta) and facies determining their formation. A. S. Zaporozhtseva. pp. 93-136.
Petrographic composition and qualitative characteristics of coals in the Chay-Tumus deposit. E. S. Korzhenevskaia. pp. 137-179.
Characteristics of the initial vegetable material of coals in the Chay-Tumus deposit. I. N. Drozdova. pp. 181-189.

RECENT TRANSLATIONS IN GEOLOGY

A review of the Translation Services

This part of the Reference Section is devoted each month to a listing of the new translations of geologic significance which have become available from sources other than IGR and the established cover-to-cover journals in geology. This is done to accomplish several purposes: 1) inform geologists of the foreign literature in their field available in translation, 2) provide information necessary to avoid duplication of translation effort, and 3) advise geologists of the activies of the various organizations providing translations or related services in their field.

RUSSIAN DICTIONARY

Those who read geology in the original Russian or translate may welcome the Moscow-published reissue of the two-volume "Geologicheskiy Slovar," [Geologic Dictionary], edited by T. N. Spizharskiy. Sporting royal blue covers this all-Russian equivalent of AGI's "Glossary of Geology and the Related Sciences" originally appeared in 1955 in brown binding. The new edition appears to be identical in content to the other, although the type has been reset; the difference is very slight. No change has been made in the list of associate editors.

The Spizharskiy work is not to be confused with T. A. Sofiano's "Russko-Angliyskiy Geologicheskiy Slovar'", which appeared two or three months ago. Those who translate find that the all-Russian work is a useful supplement to the other. Price on the Spizharskiy is not available at present.

Consultants Bureau Entrises, Inc. announces that its publication, Soviet Science in Translation, was discontinued with the April 1961 issue. Some of the listing of tables of contents of Soviet journals is being carried on by other agencies. The Institute for Scientific Information publishes two editions of Current Contents, one, Space and Physical Sciences and the other, Chemical Pharmaco-Medical and Life Sciences. Geologists will find comparable listings in their field in IGR's monthly listings of Library of Congress Accessions.

AGI Translation Office's new service of selling translations by individual copies ($0. 15 per manuscript page) has three more entries, which are included in this month's listings.

GEOLOGIC-TRANSLATION JOURNALS

The following journals regularly contain translations of interest to geologists. Therefore, the subsequent list of recent translations does not include articles falling within the scope of the cover-to cover programs of these journals:

Atomic Energy, published by Consultants Bureau.

Bulletin (Izvestiya) of the Academy of Sciences U. S. S. R., Geophysics Series, published by the American Geophysical Union.

Doklady of the Academy of Sciences of the U. S. S. R., Earth Sciences Sections, Geochemistry, geology, geophysics, hydrogeology, mineralogy, paleontology, petrography, lithology and permafrost), published by the American Geological Institute.

Geochemistry, published by the Geochemical Society.

Geodesy and Cartography, published by the American Geophysical Union.

Izvestiya of the Academy of Sciences of the U. S. S. R., Geologic Series, published by the American Geological Institute.

Petroleum Geology, published by the Review of Russian Geology.

Problems of the North, published by the National Research Council of Canada.

Soil Science, published by the American Institute of Biological Sciences.

Soviet Geography, selected translations and reviews published by the American Geographic Society.

Soviet Physics: Crystallography, published by the American Institute of Physics.

SOURCES OF TRANSLATIONS

The current list of recent translations is from the following:

American Geological Institute, Translations Office.

Associated Technical Services, Inc., List of Translations Nos. 90 and 91.

Atomic Energy Commission Translations List No. 52, March 31, 1961

Oklahoma Geological Survey, suggested listings.

Technical Translations, v. 5, nos. 11 and 12.

An index of sources and addresses will be found at the end of the list of translations.

Geologists and translators are invited to submit titles which have not been cited by services from which we compile these lists. The submittal of a copy of the translation itself will be construed as an offer for IGR to publish, make copies available at cost of reproduction and/or consign it to a major translations repository at our discretion. Suggestions for improving this service are welcome.

RECENT TRANSLATIONS

Anonymous, 1960, A preliminary summary of hydrological survey work of a certain lead mine in Yunnan province: Ti Chih Yü K'an T'an (Chinese People's Republic), no. 7, pp. 11-14. JPRS 4318; OTS 61-11875. $0.50.

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